EVALUATION OF THE AD HOC ON-DEMAND DISTANCE VECTOR ROUTING PROTOCOL FOR MOBILE AD HOC NETWORKS

THESIS

Amber J. Rickmon, Second Lieutenant, USAF

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Amber J. Rickmon, BS

Second Lieutenant, USAF

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Amber J. Rickmon, BS

Second Lieutenant, USAF

Approved:

/signed/

Rusty O. Baldwin, Ph.D., USAF (Chairman) Date

/signed/

Barry E. Mullins, Ph.D., USAF (Member) Date

/signed/

Richard A. Raines, Ph.D., USAF (Member) Date

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Amber J. Rickmon

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Abstract

Routing protocols designed for wired networks cannot be used in mobile ad hoc networks (MANETs) due to the dynamic topology, limited throughput, and energy constraints. New routing protocols have been designed for use in MANETs, but have not been thoroughly tested under realistic conditions such as node movement, number of sources, the presence of obstacles, and node speed.

This research evaluates the performance of ad hoc on-demand distance vector routing with respect to throughput, goodput ratio, end-to-end (ETE) delay, node pair packet delivery rate, and node pair end-to-end delay. It shows these performance metrics vary significantly according to the choice of mobility model, number of sources, and the presence or absence of obstacles. The mobility model explains 68% of the variation in node pair packet delivery rate. The mobility model explains between 8% and 53% of variation in the other performance metrics. Obstacles explain between 5% and 24% of variation, and have the greatest effect on ETE delay. Finally, the number of sources explains between 8% and 72% of variation in node pair ETE delay, throughput, goodput ratio, and node pair packet delivery rate. The number of sources does not have a significant affect on ETE delay.

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I. Introduction

A mobile ad hoc network (MANET) is a collection of wireless nodes that communicate without any supporting infrastructure. Nodes in a MANET often need to communicate with other nodes that are not within their transmission range. Thus, each node in a MANET acts as a host and also forwards packets to other hosts. That is, they also act as routers.

1.1 Overview

Routing protocols designed for wired networks cannot be used in MANETs due to the network's special characteristics. MANETs have dynamic topology. Links are created and destroyed frequently as nodes move in and out of the transmission range of other nodes. Furthermore, bandwidth is limited in MANETS. Wireless transmission speeds are typically much lower than those in wired networks due to fading, interference, and noise. Additionally, nodes in a MANET often operate on batteries, thus, they are energy constrained. Routing protocols designed for MANETs must consider all of these special characteristics.

Node mobility, or how nodes move within a MANET, affects routing protocol performance [BSH03], [CBD02], [ZHR04]. Early research in this area used the random waypoint mobility model. However, this is not the way mobile nodes tend to move. New mobility models include the path model [ESB04], freeway mobility model [BSH03], city section mobility model [CBD02], reference point group mobility model

[HGP99], pursue mobility model [CBD02], and obstacle mobility model [JBA03]. It is important to choose the mobility model that closely matches expected user movement to accurately predict MANET routing protocol performance. Most MANET research is also conducted using an open area simulation, however, obstacles such as buildings, trees, and terrain are often encountered in MANETs and can impede movement as well as transmission [JBA03].

1.2 Motivation and Goals

Military units often deploy to areas without existing infrastructure to support communication. These units also tend to be mobile. It is expensive and time consuming to build the infrastructure necessary to support wired and wireless local area networks, thus, MANETs are a viable solution to the communication problem. However, it is important to understand how a particular routing protocol will perform in the situations in which it will be used.

The goal of this research is to analyze the performance of the ad hoc on-demand distance vector (AODV) routing protocol while operating using mobility patterns. Measuring the effect node mobility has on routing protocol performance gives insight to which routing protocol to use in different situations.

1.3 Thesis Organization

This chapter introduces MANETs and presents motivation for this research. Chapter II introduces common routing protocols and mobility models. It also presents the results of other MANET research. Chapter III provides the methodology used to conduct this research. Chapter IV presents and analyzes the results. Chapter V draws conclusions based on the research results and provides areas for future research.

II. Literature Review

This chapter provides an overview of MANET routing protocols. Dynamic source routing is explained as an example of an on-demand routing protocol. A description of optimized link state routing is provided as an example of a table-driven routing protocol. Ad hoc on-demand distance vector routing is explained in detail because it is the focus of this study. This chapter also introduces the reference point group mobility model, the obstacle model, and several other mobility models used in MANET research. The results of current MANET mobility studies are presented last.

2.1 MANET Routing Protocols

Routing is “the process in which a route from a source to a destination node is identified and is achieved either by computing all routes before and prestoring them or computing them when needed [RoT99].” Routing in ad hoc networks typically has the following goals [RoT99]:

(1) distributed route computation,
(2) route computation based on local state,
(3) minimizing the number of nodes involved in route computation,
(4) routes to destinations, and not to portions of the network without traffic,
(5) avoiding stale routes and eliminating them quickly,
(6) avoiding broadcasts,
(7) converging to optimal routes when topology stabilizes, and
(8) having backup routes available.

Routing protocols are either proactive or reactive. Proactive protocols continuously discover routes. They attempt to have routes available and ready to use before they are needed. Alternatively, reactive protocols only perform route discovery as needed. Purely reactive protocols are not efficient in MANETs because they often take too long to discover a route. On the other hand, purely proactive protocols are not efficient because they can needlessly use too much of the network's bandwidth and energy. Routing protocols can also be classified as table-driven or source-initiated (on-demand) protocols. Table-driven routing protocols are proactive [RoT99]. They maintain tables with routing information including routes to all other nodes in the network. When the topology changes, they propagate updates throughout the network. Table-driven routing protocols include optimized link state routing (OLSR), destination-sequenced distance vector (DSDV), cluster-head gateway switch routing (CGSR), and wireless routing protocol (WRP).

Source-initiated on-demand routing, on the other hand, only creates routes as needed [RoT99]. When a route is needed, a node invokes a route discovery procedure. Routes are maintained as long as there is a path to the destination, or as long as the route is needed. The on-demand routing protocols include ad hoc on-demand distance vector (AODV) routing, dynamic source routing (DSR), temporally ordered routing algorithm (TORA), associativity-based routing (ABR), and signal stability-based routing (SSR).

Hybrid routing protocols initiate route discovery procedures on demand, but limit the search cost [RoT99]. Hybrid protocols include zone routing protocol (ZRP), fisheye state routing (FSR), landmark routing (LANMAR), location-aided routing (LAR), distance routing effect algorithm for mobility (DREAM), relative distance microdiscovery ad hoc routing (RDMAR), and power aware routing.

2.2 Dynamic Source Routing

This description of DSR is derived from [JMH03] and describes how DSR is implemented when operating with the IEEE 802.11 MAC layer which requires all links to be bidirectional. Dynamic source routing (DSR) is an on-demand routing protocol designed for use in MANETs. It uses route discovery and route maintenance to send packets in a MANET. Route discovery is used by a source node to find a route to an unknown destination. Route maintenance is used to determine if a route to the destination is still available. If a route becomes unavailable, the source node can use another known route to the destination or can invoke route discovery to find a new route.

2.2.1 Route Discovery

A node initiates the route discovery process by sending a route request. The route request includes the source node, target node, a unique identifier, and a list of intermediate nodes that have processed the route request. The source sends the route request as a local broadcast, so it is received by nodes that are within its wireless transmission range. Some nodes within the transmission range may not receive the packet due to interference.

When a node receives a route request and it is the target node, it will send a route reply. The route reply also contains a list of the intermediate nodes in the route. When the initiator of the route request receives the route reply, it caches the route. Since the IEEE 802.11 MAC protocol supports bidirectional links, the target node sends the route reply using the reverse route. However, if bidirectional links are not supported, then the target node will either use a route in its cache or initiate a route discovery back to the initiator of the route request.

If the node is not the target node, it determines if it has recently seen the same route request by examining entries in its route request table from the same initiator node with the same identifier and target address. The receiving node also checks if its address is already listed in the route record. If the receiving node has recently seen the request or is already in the route record, it discards the route request. Otherwise, it appends its address to the route record and increases the Opt Data Len field by 4 (the length of its address).

If the initiator of a route request does not receive a route reply before timing out, it will resend the route request. To limit the number of route discoveries, the time out period is doubled for each successive route request for the same target. Packets waiting to be sent to the target are held in a send buffer, as are additional packets received for this destination.

A node may also cache routes from packets it receives. Since the IEEE 802.11 MAC protocol supports bidirectional links, the forward and reverse routes are cached. However, if the packet contains a route reply, only the links that have been traversed are cached. The link that the packet traversed to reach the node is also cached.

DSR allows a node to send a route reply using cached routes. A node receiving a route request searches its route cache for a route to the target. If a route is found, the cached route is appended to the end of the list of nodes that the route request traversed. Before sending the route reply, the node must verify the list of nodes being returned does not contain any duplicates. If duplicates are found, the node removes them. If the responding node is still in the list of nodes, it will send the route reply. If the responding node is not in the list, it cannot send the route reply and will forward the route request.

Route reply storms are possible if multiple nodes approximately the same distance from the initiating node have cached routes. If they all immediately reply with a cached route, collisions will occur. DSR attempts to prevent this by delaying route replies from cached routes. The delay is proportional to the number of hops in the route minus one plus a random number between 0 and 1. Since the delay is proportional to the number of hops, shorter routes will arrive at the initiating node first. Additionally, since nodes put themselves into promiscuous mode during the delay period, a node that receives a packet from the initiator node to the target with a source route with the same number or fewer hops will not send its route reply.

The time-to-live (TTL) field in the IP header limits the number of hops taken by a route request. The TTL field can be set to 1 for a non-propagating route request. This allows the initiating node to determine if the target is a neighbor or if a neighbor has a route to the target. In this way, the initiating node uses neighboring caches as an extension of its own. The TTL field can also be used to implement an expanding ring search by initially setting the field to 1 and doubling it each time there is not a response.

2.2.2 Route Maintenance

Each node that originates or forwards a packet using a source route must ensure that data can be passed on the link from that node to the next hop. Acknowledgements confirm the link is operational. When DSR is used in conjunction with the IEEE 802.11

MAC protocol, the link-layer frame acknowledgements confirm receipt. Passive acknowledgements can also be used. That is, when a node detects the next hop node forwarding the packet it assumes the data was transmitted.

When a node determines that the next hop link is broken, it removes the link from its route cache and returns a route error message to the source node. If packet salvaging is enabled, the node that determined the failure will look for another route to the destination in its route cache. If found, it will replace the source route with the new route and forward the packet to the next hop. A salvage count is maintained in order to prevent salvaging loops. If the packet cannot be salvaged, the source node must initiate a new route discovery and resend the packet.

When a node determines the next-hop in a path is broken, it removes all packets from the queue that use the next hop and sends a route error message to each source. Only one route error message is sent to each source, even if there are multiple packets for a particular source. When a source node receives a route error message, it piggybacks the route error on the next route request it sends to increase the spread of route error messages.

Automatic route shortening prevents packets from making unnecessary hops. A node set in promiscuous mode receives packets containing source routes. If the node finds itself in the portion of the source route that has not been reached, it can forward the packet removing the unnecessary nodes. After forwarding the packet, the node sends a gratuitous route reply to the original sender. The route reply contains the route up to the node transmitting the packet plus the remaining route from the node sending the route reply to the destination.

2.3 Optimized Link State Routing

This description of optimized link state routing (OLSR) is derived from [ClJ03]. Furthermore, it only includes the core functionality of OLSR which is sufficient to provide routing in a MANET. OLSR is a table-driven, proactive routing protocol designed for MANETs. Since it is a proactive protocol, routing information is shared regularly and is ready when needed.

2.3.1 Multipoint Relays

OLSR limits flooding of control traffic by using multipoint relays (MPR). Each node chooses a set of MPRs from its set of 1-hop neighbors with bi-directional links. Each node selects its MPR set such that all 2 hop neighbors can be reached by at least one MPR. Multipoint relays re-transmit all broadcast messages that are received from their multipoint relay selectors. Other nodes process the messages, but do not retransmit them. This limits the number of retransmissions in each area of the network. Thus, the smallest possible set of MPRs is desired in order to minimize control overhead.

Multipoint relays are also used in route calculation. When a node advertises link information it only advertises information about links to MPR selectors. Routes are then calculated using this information. Thus, a packet travels from source to destination only through multipoint relays. Since the link between a MPR and its MPR selector is bi-directional, packets are always sent on bi-directional links.

2.3.2 OLSR Packet Format

All data related to OLSR uses the same packet format (Figure 2.1). The packet header has a packet length (in bytes) and a unique packet sequence number. Each packet can have one or more messages, and each message has a message header. The message type field indicates the type of the OLSR message. The standard OLSR messages are explained in section 2.3.4. The message size field holds the length of the message in bytes, including the message header. VTime is the length of time that the information in the message is considered valid after it is received. The originator address is the main address of the node that generated the message. Main addresses are discussed in section 2.3.4. The time to live field contains the maximum number of hops that a

<table>
<tr><th>0 1 2 3 4 5 6 7</th><th>0 1 2 3 4 5 6 7</th><th>0 1 2 3 4 5 6 7</th><th>0 1 2 3 4 5 6 7</th></tr>
<tr><td colspan="2">Packet Length</td><td colspan="2">Packet Sequence Number</td></tr>
<tr><td>Message Type</td><td>VTime</td><td colspan="2">Message Size</td></tr>
<tr><td colspan="4">Originator Address</td></tr>
<tr><td>Time To Live</td><td>Hop Count</td><td colspan="2">Message Sequence Number</td></tr>
<tr><td colspan="4">Message</td></tr>
<tr><td>Message Type</td><td>VTime</td><td colspan="2">Message Size</td></tr>
<tr><td colspan="4">Originator Address</td></tr>
<tr><td>Time To Live</td><td>Hop Count</td><td colspan="2">Message Sequence Number</td></tr>
<tr><td colspan="4">Message</td></tr>
</table>

(etc.)

Figure 2.1: OLSR Packet Format [ClJ03]

message can take. It is decremented by 1 each time the message is forwarded. Conversely, the hop count field begins at 0 and is incremented each time the message is forwarded. The message sequence number is a unique identifier.

When a node receives a packet it examines each message header. To avoid re-processing messages each node maintains a Duplicate Set. The duplicate contains tuples with the originator address, the message sequence number, a boolean indicating whether the message has been retransmitted, a list of the interfaces on which the message has been received, and an expiration time. If a message is in the Duplicate set, it is silently discarded. Otherwise, the node will process the message, and forward the message only if it is an MPR for the sender.

2.3.3 Information Repositories

OLSR nodes accumulate information about the network through OLSR control messages. The information is stored in several information bases. The multiple interface association information base stores "Interface Association Tuples" for each destination in the network. This table has one entry for each OLSR interface. Since each node may have multiple OLSR interfaces, this table may have multiple tuples for one physical node. Each entry has the interface address, the main address of the node, and the time that the tuple expires.

The local link information base stores information about links to neighboring nodes. "Link Tuples" have the form (L_local_iface_addr, L_neighbor_iface_addr, L_SYM_time, L_ASYM_time, L_time). L_local_iface_addr and L_neighbor_iface_addr are the interface addresses of the local node and the neighboring node, respectively.

L_SYM_time is the time until which the link is considered symmetric, and L_ASYM_time is the time until which the neighboring interface can be heard. L_time denotes the time that the tuple expires.

The neighborhood information base contains information about neighbors, 2-hop neighbors, MPRs, and MPR selectors. The node stores each neighbor's main address, status (symmetric or asymmetric), and the willingness of the neighbor to carry traffic for other nodes. The 2-hop neighbor set tuples have the 2-hop neighbor address, the main address of the 1-hop neighbor that reaches the 2-hop neighbor, and the expiration time of the tuple. The MPR set is the set of neighbors selected as MPRs. The MPR selector set stores the main address of neighbors which have selected the node as an MPR. It also stores the time at which the tuple expires.

The topology information base has topology information about the network. Topology set tuples have the destination address, the address of an MPR node for the destination, the sequence number, and the time that the tuple expires. The topology set may have multiple tuples for each destination.

2.3.4 OLSR Message Formats

Hello Messages

Hello messages are sent periodically to accommodate link sensing, neighbor detection, and MPR selection signaling. Hello messages are sent as the data portion of the OLSR packet format. The TTL field in the message header is set to 1 so the packet is not forwarded. The hello message format is shown in Figure 2.2. The "Reserved" field is filled with zeros. Htime gives the time until the node interface generates the next hello message. The “Willingness” field specifies how willing the node is to forward traffic for other nodes. Willingness is measured on a scale from 0 to 7, where 0 indicates that the node is not willing to forward packets and 7 indicates that the node is willing to forward packets for all nodes. The Link Message Size field contains the size of the message in bytes. It is measured from the beginning of the Link Code field to the beginning of the next Link Code field or the end of the message. The “Link Code” field specifies information about the link between the sender and the list of neighbor interface addresses.

The link code can be unspecified, asymmetric, symmetric, and lost. An unspecified link indicates that no information is known about the link. An asymmetric link indicates that the neighbor interface is heard, but it is unknown if the neighbor can hear the node sending the message. A symmetric link indicates that the node and its neighbor can both hear each other. Finally, a lost link indicates the link has been lost.

<table>
<tr><td>0 1 2 3 4 5 6 7</td><td>0 1 2 3 4 5 6 7</td><td>0 1 2 3 4 5 6 7</td><td>0 1 2 3 4 5 6 7</td></tr>
<tr><td colspan="2">Reserved</td><td>Htime</td><td>Willingness</td></tr>
<tr><td>Link Code</td><td>Reserved</td><td colspan="2">Link Message Size</td></tr>
<tr><td colspan="4">Neighbor Interface Address</td></tr>
<tr><td colspan="4">Neighbor Interface Address</td></tr>
<tr><td colspan="4">...</td></tr>
<tr><td>Link Code</td><td>Reserved</td><td colspan="2">Link Message Size</td></tr>
<tr><td colspan="4">Neighbor Interface Address</td></tr>
<tr><td colspan="4">Neighbor Interface Address</td></tr>
<tr><td colspan="4">(etc.)</td></tr>
</table>

Figure 2.2: OLSR Hello Message Format [ClJ03]

Nodes use hello messages to populate the neighbor table. They record information about the 1-hop neighbor, the link status, and the 2-hop neighbors that the 1-hop neighbor reaches. This is used to select multipoint relays because the MPRs must be able to reach all 2-hop neighbors.

Multiple Interface Declaration Message

Each node using OLSR may have multiple OLSR interfaces. However, each node must be identified by one address. Thus, each node selects the address of one of its OLSR interfaces as its main address. This information is conveyed to other nodes in the network through multiple interface declaration (MID) messages. A MID message lists the address of all interfaces other than the main address of the originating node. The main address is the "originator address" in the message header.

Topology Control Message

All nodes selected as an MPR send topology control (TC) messages. A TC message has an advertised neighbor sequence number which is incremented each time the node detects a change in its advertised neighbor set. This allows a node receiving a TC message to decide if the information is more recent than what it already has. A TC message also lists the main address of all nodes in its MPR selector set. The main address of other neighbor nodes may also be included. TC messages are flooded to all nodes in the network through MPRs.

2.4 Ad hoc On-Demand Distance Vector Routing

This description of ad hoc on-demand distance vector (AODV) routing is derived from [PBD03]. AODV is an on-demand routing protocol used in MANETs. Routes are created as needed by a source node, that is, when the destination is not known to the source, when a route to the destination has expired, or when a route is marked as invalid.

A destination is not known to a source when it receives the first packet to a new destination. A route stored in a node's route table expires when it has not been used before the time in the Active Route Lifetime field. After a route has expired it is marked invalid. A route is also marked invalid when a link breaks or is deactivated. Invalid routes cannot be used to send data packets, but they can be used for route repair or future route requests.

2.4.1 AODV Sequence Number

Each node using AODV maintains a route table. Every entry in the route table contains a destination sequence number. This destination sequence number is the latest sequence number for the node listed as the destination node in the destination IP address field. Each node in the network maintains its own sequence number and increments it before originating a route discovery. Before a destination node originates a route reply, it also updates its sequence number if its current sequence number is lower than the destination sequence number contained in the route request.

The destination sequence number identifies the most current route information. When a node receives information about a destination, it compares the incoming destination sequence number to the sequence number contained in its route table. If the sequence number contained in the route table is greater, the incoming information is stale and is dropped. Otherwise, the information in the route table is updated and the new destination sequence number is stored. The only other reason a node might change a sequence number is for a lost or expired link to the next hop. In this case, the node increments the sequence number and marks the route as invalid. When a node receives information about a destination that is marked as invalid, the node updates its route table if the destination sequence number is at least equal to the destination sequence number in the invalid route table entry.

2.4.2 Route Request Messages

A node sends a route request (RREQ) when it needs a route to a destination. The format of a route request messages is shown in Figure 2.3. The Destination Sequence Number field contains the last known sequence number for the destination. If the destination sequence number is not known, then the “unknown sequence number”, U, flag is set. The other flag fields are explained later in this section. The Originator Sequence Number is the current sequence number of the node originating the RREQ. A RREQ ID is maintained by each node. It is incremented each time the node sends a RREQ. The Hop Count field is set to zero.

The originating node sends the RREQ using an expanding ring technique (if it does not have an invalid route table entry for the destination) by using the IP header time to live (TTL) field. Initially, the TTL field is set to TTL_START and the RREQ is sent. The first time the RREQ is sent, the source node waits NET_TRVERSAL_TIME milliseconds for a route reply (RREP). If the RREQ times out without a RREP, the source increments the TTL field by TTL_INCREMENT and resends the RREQ. The second time a RREQ is sent the source node waits 2*NET_TRAVERSAL_TIME milliseconds. The wait time follows a binary exponential backoff sequence for each retransmission of a RREQ until the maximum number of retransmissions, RREQ_RETRIES. When TTL reaches TTL_THRESHOLD, all future requests are sent with the TTL field set to NET_DIAMETER. When a new route to a destination with an invalid route table entry is needed, the TTL is initially set to the Hop Count of the route table entry plus TTL_INCREMENT and the TTL is incremented as described previously. After routing table entries are marked invalid, they are deleted after DELETE_PERIOD seconds.

0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7

Type	J|R|G|D|U	Reserved	Hop Count
RREQ ID			
Destination IP Address			
Destination Sequence Number			
Originator IP Address			
Originator Sequence Number			

Figure 2.3: AODV Route Request Message Format [PBD03]

2.4.3 Route Reply Messages

Route replies define a route from the source node to the destination node. A RREP can be from the destination or from an intermediate node. An intermediate node that has a route to the destination can send a RREP if the route is “fresh enough” and the “destination only”, D, flag in the route request is not set. A route is “fresh enough” if the sequence number of the valid route in the route table is greater than or equal to the sequence number in the RREQ.

<table>
<tr><td colspan="5">0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7</td></tr>
<tr><td>Type</td><td>R|A</td><td>Reserved</td><td>Prefix Sz</td><td>Hop Count</td></tr>
<tr><td colspan="5">Destination IP Address</td></tr>
<tr><td colspan="5">Destination Sequence Number</td></tr>
<tr><td colspan="5">Originator IP Address</td></tr>
<tr><td colspan="5">Lifetime</td></tr>
</table>

Figure 2.4: AODV Route Reply Message Format [JBD03]

The RREP message format is shown in Figure 2.4. The Destination IP Address and Originator IP Address are copied from the RREQ. If the RREP is sent from the destination, the destination compares its sequence number to the Destination Sequence Number of the RREQ. If the number in the RREQ is one greater than the destination's actual sequence number the destination node increments its sequence number. The destination's sequence number is entered in the RREP message. The destination also sets Hop Count to 0 and enters its MY_ROUTE_TIMEOUT value in the Lifetime field.

If an intermediate node generates the RREP, it sets the Destination Sequence Number to the one in its route table entry for the destination. The intermediate node updates its route table by adding the route request's previous hop to the precursor list of the forward route, and adds the next hop of the forward route to the precursor list for the reverse route. Hop Count is set to the hop count in the intermediate node's route table entry for the destination. The Lifetime field is set to the difference between the route expire time and the current time. If the 'G' flag is set, the intermediate node sends a gratuitous RREP to the destination. The gratuitous RREP is sent to the destination as if it had sent a RREQ to the originator node and the intermediate node sent a reply.

RREPs also update information in intermediate nodes' routing tables. First, a route to the previous hop is added to the route table if one does not already exist. A route is also created to the destination node if it doesn't already exist. If the route does exist, the route entry can be updated with the information contained in the RREP. The node forwards the RREP and adds the next hop for the RREP to the precursor list of the destination node. A node can forward a RREP with the 'A' flag set, requiring a route-reply acknowledgement. The 'A' flag is typically used if a link is unstable.

2.4.4 Hello Messages and Route Error Messages

Hello messages are used to maintain connectivity information of neighbors that are part of active routes. A node checks if it has sent a broadcast (i.e., a RREQ or another layer 2 message) every HELLO_INTERVAL milliseconds. If it has not, it will send a Hello message with TTL = 1. Neighbors that receive a Hello message ensure they have an active route to the sender. If a route does not exist, one is created. If a route already exists, the lifetime is increased to ALLOWED_HELLO_LOSS * HELLO_INTERVAL.

A node initiates processing for a route error (RERR) message when it detects a link break while transmitting data, if it gets a data packet destined for a node for which it does not have an active route, or it receives a RERR from a neighbor. The node must first identify the unreachable destinations. In the case of a link break, all nodes that use the unreachable neighbor as a next hop are unreachable. If the node received a packet for which it does not have a route, the destination of that packet is unreachable. If the RERR was received from another node, then the unreachable nodes are those listed in the RERR and those that sent the RERR as the next hop.

The RERR is sent to all nodes in the precursor list of a route table entry to one of the unreachable destinations. The precursor list in route table entries contains the neighboring nodes that have been sent a RREP from the current node. If only one node needs to receive the RERR, it is sent unicast. Otherwise, the RERR is sent as a broadcast with all of the unreachable destinations listed in the packet. The RERR message format is shown in Figure 2.5. DestCount contains the number of destinations listed in the packet. If the RERR is being forwarded, the destination sequence numbers are simply copied, otherwise, they are incremented before placing them in the RERR. Entries to the unreachable destinations are marked as invalid. Finally, the Lifetime field is set to current time plus DELETE_PERIOD, so entries will only be deleted after DELETE_PERIOD seconds. The N flag is a ‘no delete’ flag and is explained later.

0 1 2 3 4 5 6 7	0	1 2 3 4 5 6 7 0 1 2 3 4 5 6 7	0 1 2 3 4 5 6 7
Type	N	Reserved	DestCount
Unreachable IP Address (1)			
Unreachable Destination Sequence Number (1)			
Additional Unreachable IP Addresses (if needed)			
Additional Unreachable Destination Sequence Number (if needed)			

Figure 2.5: AODV Route Error Message Format [JBD03]

A node that detects a link break may attempt to repair the link if the destination is no more than MAX_REPAIR_TTL hops away. The node increments the sequence number and send a RREQ with the TTL field set to max(MIN_REPAIR_TTL, 0.5*#hops) + LOCAL_ADD_TTL. #hops is the number of hops to the originator of the undeliverable packet. If a RREP is not received during the first wait period, then a RERR packet is sent.

If the node receives a route to the destination, it compares the hop count of the new route to that of the old route. If the new route is longer, a RERR message is sent to the originator of the undeliverable packet with the ‘no delete’ flag set, which indicates the originating node should not delete the route, but should process it and forward the RERR message. The originating node may choose to discover a new route if the RERR message originated at the next hop to the destination. Other destinations made unreachable by the link break are marked as invalid, but they may also be marked as locally repairable.

2.5 Mobility Models

After nodes are placed in a MANET simulation, a mobility model will control the movement of the nodes. The mobility model controls factors such as node speed and direction and how the speed and direction vary with time. It also controls the behavior of a mobile node when it reaches a simulation boundary. The following mobility models have been proposed to model node movement.

2.5.1 Reference Point Group Mobility Model

The reference point group mobility (RPGM) model defines the movement of groups within a MANET [HGP99]. The logical “center” of each group defines the motion of the entire group and the group moves according to a group motion vector. Each node has a reference point that follows the group movement. As the logical center moves, the reference points move. Each node’s position is obtained by adding a random motion vector to the node’s reference point location. The random motion vector’s length is uniformly distributed between 0 and some radius centered at the reference point. The random motion vector’s direction is uniformly distributed between 0 and 360 degrees.

Group movement in the RPGM model is driven by a set of check points that correspond to time intervals. When the group center reaches a check point, it computes the next motion vector based on the current and next check points and the time interval.

The RPGM model can be used to model an In-Place Group Model whereby an area is divided into regions and each group occupies a different region [HGP99]. Although each group is in its own region, they may all be performing the same task. This type of model, for example, can represent Army battalions searching for land mines. The Overlap Mobility Model models several groups occupying the same area, but accomplishing different tasks such as in disaster recovery situations. The different groups could be a rescue team, medical team, and psychological team. The RPGM model can also be used as a Convention Mobility Model. At a convention, several groups give demonstrations while groups of attendees roam around at varying speeds.

2.5.2 Obstacle Mobility Model

An obstacle mobility (OM) model is designed to mimic real-world topographies [JBA03] including buildings and other structures that impede movement or signal propagation. Obstacles can be different shapes and sizes and can be placed anywhere within a region.

The paths between the obstacles are defined by a Voronoi Diagram of the obstacle corners. The Voronoi Diagram is “a planar graph whose edges are line segments that are equidistant from two obstacle corners” [JBA03]. Movement through buildings is allowed through doorways on the sides of the buildings. Nodes move to their destination using the shortest path, and may travel through other buildings to reach their destination.

At the beginning of the simulation, obstacles are placed and paths are computed. Mobile nodes are initially distributed randomly along the paths. They choose a destination and compute the shortest path. After reaching the destination, a node pauses before choosing another destination.

2.5.3 Other Mobility Models

Typical mobile nodes travel along fixed paths. For example, cars travel on roads, trains on tracks, and people on sidewalks. The path model is designed to model this behavior [ESB04]. In the path model, only a certain number of paths leave each location. Each time a node reaches a location it picks its next location from a set of available locations. The paths to the next location are straight lines. It is therefore necessary to specify the number of locations and the number of locations that can be reached from each location or the "location degree."

The random waypoint mobility model pauses between periods of movement [CBD02]. A mobile node is stationary for some pause time, and then chooses a random destination. The node moves to the destination with a particular speed (uniformly distributed between some minimum and maximum speed). After reaching the destination, the mobile node pauses and then chooses another location.

The freeway mobility model models traffic on a freeway [BSH03]. In this mobility model there are several freeways that have lanes in both directions. A mobile node is restricted to its lane, and its velocity is a function of its previous velocity. When two nodes share the same lane, the velocity of the following node cannot exceed the velocity of the front node when within the safety distance.

The Manhattan model simulates mobility in an urban area [BSH03]. This model uses a map with roads that run north-south and east-west. Each street has one lane in each direction. Nodes may change direction or go straight at each intersection. The probability of going straight is 0.5, while the probability of turning left is 0.25 and the probability of turning right is 0.25. A node's velocity during a time period depends on its velocity during the previous time period. Like the freeway model, a node's velocity is dependent on nodes in front of it in the same lane.

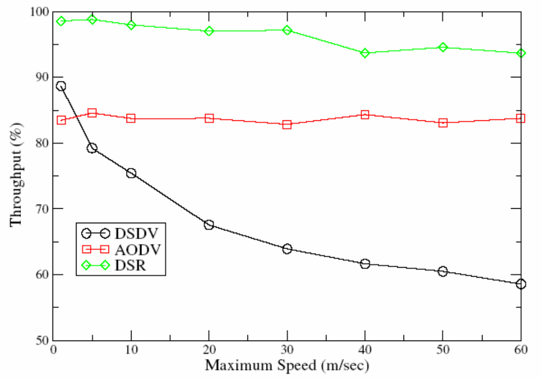
In the random walk mobility model, a node randomly chooses a speed and direction to travel [ESB04]. The speed is between a minimum speed and maximum speed, and the direction is between 0 and 2π. Generally, a new direction and speed is chosen after a constant time, but some variations choose a new direction and speed after the node travels a constant distance.

Typically, a city has several points of interest that people wish to visit instead of traveling at random [ESB04]. The location model simulates this behavior. At the beginning of simulation some number of locations is specified from which the model randomly chooses locations. Each time a node needs a new destination, it chooses from the predetermined set of locations and moves directly to the new destination.

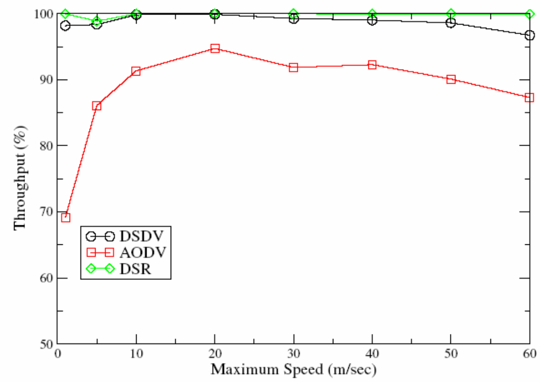
The home-work model is based on the fact that most people travel to some locations with high frequency, i.e. home, work, store or restaurant [ESB04]. At the beginning of the simulation each node picks a set of preferred locations, and randomly chooses locations from this set throughout the simulation.

2.6 Related Research

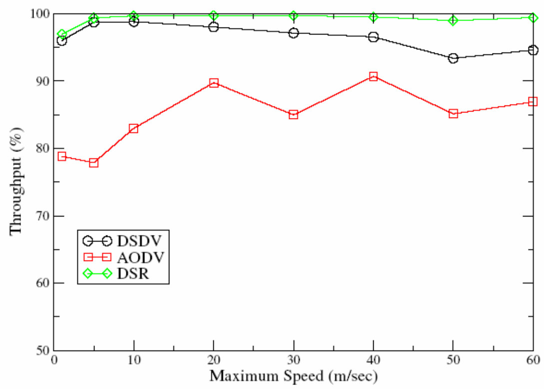
The mobility model used in a simulation affects the performance of the routing protocol. A comparison of AODV, DSR, and DSDV using random waypoint, RPGM, freeway, and Manhattan models shows that all routing protocols have the highest throughput and the lowest overhead with RPGM [BSH03]. Figure 2.6(b) shows RPGM with a single group achieves the highest throughput at most maximum speeds, and Figure 2.6(g) shows low routing overhead. RPGM with four groups also has a high throughput and low routing overhead (Figures 2.6(c) and 2.6(h)). The freeway model shows high throughput (Figure 2.6(d)), but also has a high routing overhead (Figure 2.6(i)). In most cases DSR has the highest throughput, but AODV achieves higher throughput in the Manhattan mobility model as seen in Figure 2.6(e). DSDV has the least overhead of all three routing protocols when using the freeway or Manhattan models (Figure 2.6(i,j)), while DSR has the least overhead with the other two mobility models (Figure 2.6(f-h)). This shows that neither on-demand nor table-driven protocols perform best in all cases. Additionally, a protocol with the least overhead does not always achieve the highest throughput. For example, DSDV has the least overhead and the least throughput in the freeway model (Figures 2.6(i) and 2.6(e)).



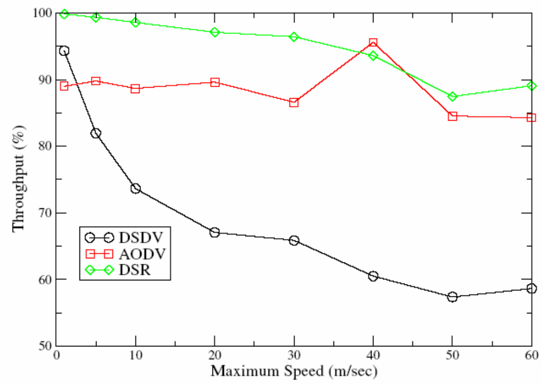
(a) Random Waypoint: Throughput



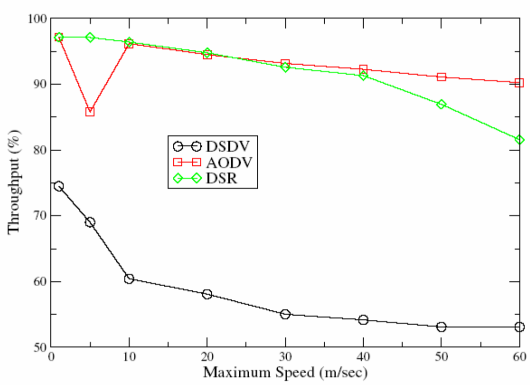
(b) RPGM: (Single Group) Throughput



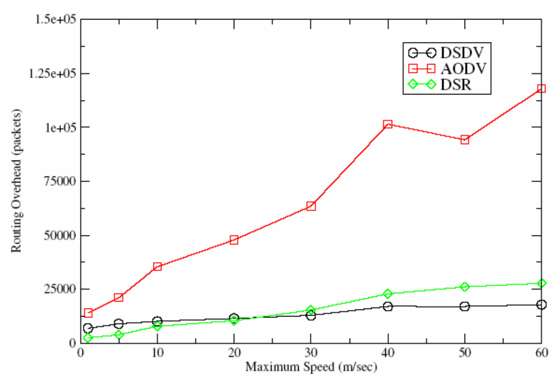
(c) RPGM: (4 Groups) Throughput



(d) Freeway: Throughput

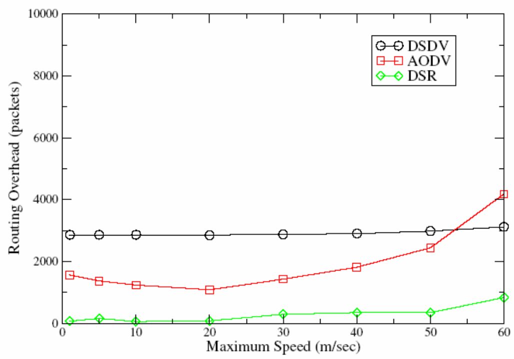


(e) Manhattan: Throughput

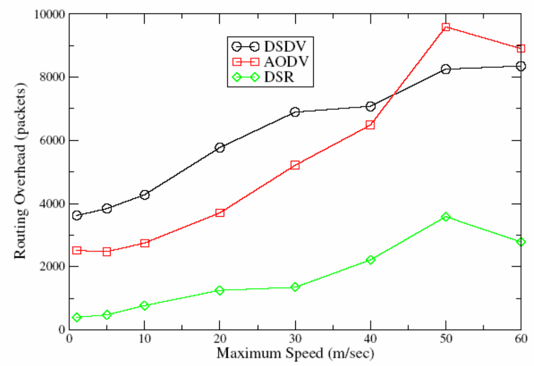


(f) Random Waypoint: Routing Overhead

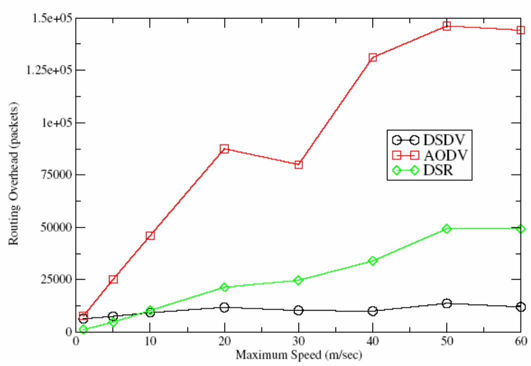
Figure 2.6: Performance Graphs [BSH03]



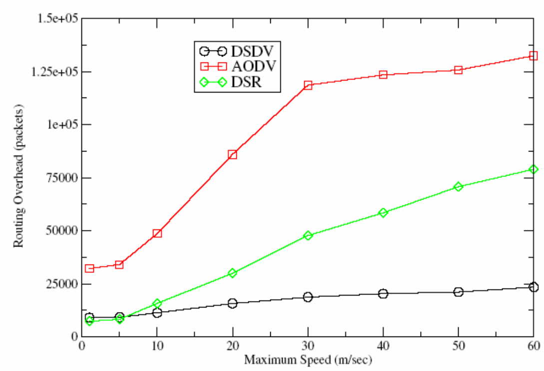
(g) RPGM (1 Group): Routing Overhead



(h) RPGM (4 Groups): Routing Overhead



(i) Freeway: Routing Overhead



(j) Manhattan: Routing Overhead

Figure 2.6: Performance Graphs [BSH03]

The TRansportation ANalysis SIMulation System (TRANSIMS) also attempts to model real world mobility. TRANSIMS models provide information about a region's individuals, their activities, and the transportation infrastructure. It simulates the movement of individuals, mimicking the traveling and driving behavior of real people.

Spatial analysis can be used to compare mobility models without running network simulations [ESB04]. Comparing the radio connected graphs generated by the mobility models shows whether the models use the simulated region in the same way. If the graphs are similar, then simulation results should also be similar.

Sub-region visitation is one way to compare the graphs [ESB04]. A sub-region is considered visited if any node was at that point at any time. The TRANSIMS graph has distinct paths, as one would expect to see in a city map. Conversely, the random way point and random walk models show complete coverage. The location model does not cover the entire region, and it is not possible to clearly identify paths. The path model is the most similar to the TRANSIMS data as routes are clearly discernible when using the path model.

Using percent freespace as a metric, the path model is also the most similar to the TRANSIMS data. Percent freespace is the percentage of the area that has been visited as time passes. The TRANSIMS data has approximately 30% coverage. The random way point and home-work models quickly converge to 100% coverage. The random walk and location models converge slower, with the location model reaching 96% coverage. The path model converges at approximately 70% coverage.

Spatial distribution is a metric that counts the number of nodes that visit each location [ESB04]. This shows the paths, if any, that are traveled most often. TRANSIMS data shows several peaks, identifying regions that are visited the most while the random walk and random way point data do not show peaks. This means that they achieve relatively uniform visitation. The home-work model shows some small peaks, but the location and path models are the most similar to TRANSIMS data.

Ad hoc routing protocol performance varies when using different mobility models [CBD02]. Performance metrics used to measure performance for this study include end-to-end delay, data packet delivery ratio, hop count, and control packet overhead. The performance can also change significantly when using the same mobility model with different parameters. When performing MANET studies, the mobility model that most closely matches the scenario should be used. Furthermore, if a group mobility model is used, using intergroup communication versus intragroup communication can have a significant impact. Finally, if the expected real-world situation is not known, then researchers should consider several mobility models and make an informed decision.

2.7 Summary

This chapter begins with a discussion of MANET routing protocols. Dynamic source routing and ad hoc on-demand distance vector routing are explained in detail. Then, a description of several mobility models is given. Finally, the results of current research in this area are presented.

III. Methodology

This chapter provides the methodology to evaluate the effect of mobility on ad hoc on-demand distance vector routing. It provides the necessary information to duplicate this experiment

3.1 Problem Definition

3.1.1 Goals and Hypothesis

MANETs cannot use the same routing protocols as wired networks or wireless local area networks due to inherent limitations of the mobile nodes and the dynamic nature of MANET topology. Several routing protocols have been designed for use in MANETs. The goal of this research is to analyze the performance of ad-hoc on-demand distance vector routing. Specifically, the goal is to measure the effect of node mobility on this MANET routing protocol.

AODV is an on-demand routing protocol. As such, the routing overhead is likely to be low. This also means that the "goodput" ratio will be high compared to what would be expected from a system with a significant amount of routing overhead packets such as a network using a table-driven routing protocol. End-to-end delay is expected to be higher using the path mobility model versus the reference point group mobility model since nodes using the RPGM model form groups and will be closer to each other. Node pair packet delivery rate is likely to be higher for flows in the same group using RPGM because there are fewer hops, the nodes are closer to each other, and route discovery is quicker. However, collisions due to the nodes being concentrated in groups may cause more retransmissions. Node pair end-to-end delay for two nodes in the same group is expected to be lower for the same reasons.

3.1.2 Approach

To accomplish the research goal, performance metrics are observed under operating conditions. AODV is modeled in simulations while mobile nodes move around the simulation area according to the RPGM model and the obstacle mobility model. Performance metrics measured during network simulations are used to evaluate the effect of node mobility.

3.2 System Boundaries

As depicted in Figure 3.1, the system under test (SUT) for this study includes the mobile nodes and obstacles within the boundaries of the MANET operations area. The mobility model (i.e., the way a node moves) and the 802.11 MAC layer are also included. The 802.11 MAC layer provides functionality to support wireless networks. The component under test is AODV.

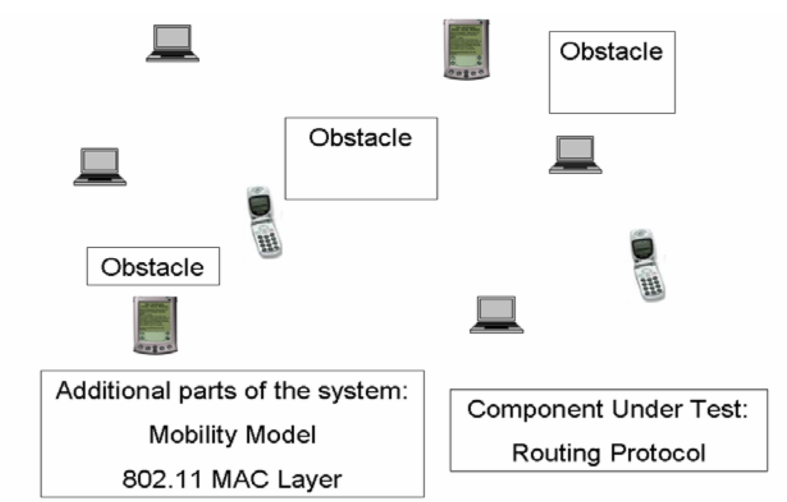


Figure 3.1: System Under Test

3.3 System Services

The system provides a data transfer service. Success is defined as the destination node receiving the data. Failure is defined as the data not reaching the destination node. Failure can be due to congestion in the network, outside interference, a route not existing from the source to the destination, a route break during transmission, or exceeding retransmission limit.

Network congestion can cause a failure when two nodes within each other's transmission range simultaneously send packets causing a collision. Devices that are not a part of the network can cause outside interference if they operate within the same radio frequency range. Due to node mobility, partitions may exist in the network. A network partition occurs when a subset of nodes is completely disconnected from the rest of the network. Nodes belonging to different partitions cannot communicate. Another problem caused by node mobility is route breaks. A path that exists when a packet is first sent can be broken during transmission. MANET routing protocols attempt to retransmit a packet when it does not reach its destination, but there is a retransmission limit or a limit on the number of times that a source node will retransmit a packet before dropping it. For the purpose of this research, all failures are treated the same.

3.4 Workload

The workload for the system is the data that passes through the MANET. This data includes user data and routing protocol data. User data is information that a source node transmits to a destination node. Nodes use routing data to find paths through the network or to forward a packet to the next hop towards the destination. Routing data is either included in the header of a user data packet or in a separate packet. An example of a routing data packet is a route request packet used in AODV. The routing data in the network changes with the routing protocol used.

3.5 Performance Metrics

The following metrics are used to measure the performance of the network as a whole:

- Throughput – Throughput is defined as $S = \frac{b_{tx}}{t}$, where b_{tx} is the number of successfully transmitted bits and t is the elapsed time. Throughput is an important performance metric when studying MANETs because they have a limited amount of bandwidth.
- Goodput Ratio – "Goodput" ratio is defined as $G = \frac{db_{rx}}{rb_{tx} + db_{tx}}$, where db_{rx} is the number of data bits received by the destination nodes, rb_{tx} is the number of routing bits transmitted, and db_{tx} is the number of data bits transmitted. "Goodput" ratio measures the efficiency of the network, that is, the percent of data bits transmitted relative to all bits.
- End to End (ETE) Delay – ETE delay is measured from the time a packet arrives at the source node's routing layer to the time the packet is received at the routing layer of the destination. It is measured in seconds. ETE delay is a lower better metric and is a standard metric used to measure computer network performance.

In addition to network performance metrics there are node pair performance metrics. These are:

- Node Pair Packet Delivery Rate – Node pair packet delivery rate measures the percent of packets successfully delivered for a particular traffic flow. Packet delivery rate is $\frac{n_d}{n_a}$, where n_d is the number of successfully delivered packets and n_a is the total number of packets the source node attempts to send. For example, a MANET with 50 nodes may have a particular traffic flow between node 1 and node 50. Node pair packet delivery rate measures the percent of packets originating at node 1 that successfully reach destination node 50.
- Node Pair ETE Delay – Node pair ETE delay measures the mean delay for a particular node pair. When an attempt to send a packet fails the routing protocol attempts to retransmit the packet. The delay, then, is the elapsed time from when the packet first arrives at the source node's routing layer to when the packet is received by the destination node's routing layer. For example, consider an ad hoc network with 50 nodes. Suppose node 1 attempts to send a packet to node 50 and the first attempt fails. Node 1 resends the packet. If the second attempt is successful, the ETE Delay for this packet is the difference between when node 50's routing layer receives the packet and when the packet arrived at node 1's routing layer. Node pair ETE delay is the average of all delays associated with packets sent from node 1 to node 50.

3.6 Parameters

The parameters shown below affect the performance of the system.

3.6.1 System

- Node Movement – The mobility model used in network simulations directly affects the performance of MANET routing protocols. AODV may perform well using the random waypoint mobility model, however, it may not perform well using the reference point group mobility model. When testing a routing protocol, the node mobility model must represent the expected traffic pattern of the nodes that will use the system.
- Antenna Type – The nodes have omni-directional antennas. This means that the antennas can transmit in all directions.
- Link Type – The links in this system are bi-directional. Several MANET routing protocols require bi-directional links. For example, DSR uses source routing. A source that sends a packet must discover a path to the destination by sending route request. When a route is discovered it is transmitted back to the sender along the reverse path, thus bi-directional links are necessary.
- Transmission Range – The transmission range of the mobile nodes is 250 meters. Transmission range affects node degree, the number of nodes that can be reached from each node in the network. It also affects the amount of contention in the network. Higher transmission ranges, and thus higher node degree, means that there is a greater chance of packet collisions.

- Routing Protocol – The routing protocol for this study is AODV. It is an on demand routing protocol created for MANETs. On demand routing protocols typically have less routing overhead than table-driven routing protocols because routes are only discovered when needed. This reduces the load on the bandwidth limited wireless links and reduces power consumption.
- Number of Nodes – The number of nodes in the simulation affects the coverage of the simulation area and the node degree. Simulation area should be considered when determining the number of nodes. 50 nodes are used in the simulation because this is typical in MANET research [BMJ98], [DPR00], [JBA03].
- Node Speed – Node speed affects the performance of MANET routing protocols because it causes changes in the MANET topology. Higher node speeds cause links to break more often, while lower node speeds result in more stable networks.
- Simulation Area – The simulation area affects node degree. The number of nodes should be considered when choosing the simulation area. The simulation area is 1000 meters by 1000 meters. Again, a typical size in MANET simulations.
- Obstacles – Obstacles may be present in the MANET operation area and network traffic cannot propagate through obstacles. In this situation, traffic must be routed around the obstacles.

3.6.2 Workload

- Number of Source Nodes – Source nodes are the only nodes that generate traffic. Thus, the number of source nodes affects the amount of traffic in the network.

- Arrival Rate – Constant bit rate sources are used. Each source node creates 4 packets per second.
- Packet Size – Source data contained in packets is 512 bytes. Routing packet size varies depending on the type of packet. For example, route request messages are 24 bytes while route reply and route error messages are 20 bytes. Several other MANET studies have used 512 byte data packets [Bou04], [DPR00], [HKG01], [JBA03].

3.7 Factors

- Node Movement
    - Reference Point Group Mobility (RPGM) – The RPGM model represents group movement as well as the movement of individual nodes in the group. The obstacle mobility model drives the movement of the logical center of the group. Other group members stay within 5 meters of the logical center.
    - Obstacle Model – Node mobility is controlled according to the obstacle model from [JBA03]. The obstacle model limits node movement to paths that are defined by the location of obstacles in the simulation area. The paths are calculated by creating a Voronoi diagram.
- Number of Source Nodes
    - Light Network Load – 20 source nodes are used for a light network load.
    - Heavy Network Load – 30 source nodes are used for a heavy network load.

- Node Speed
    - Pedestrian Speed – To simulate pedestrian speeds, node speed varies between 0 and 5 meters per second.
    - Vehicle Speed – Vehicle speed varies between 0 and 20 meters per second.
- Obstacles
    - No Obstacles – This factor level models an open operation area.
    - Obstacles Present – Obstacles will be present. Obstacles will cause the traffic to be routed differently. Two nodes that are within transmission range but are separated by an obstacle will not be able to receive the transmission directly. The traffic will have to be routed by an intermediate node. Obstacles will cover 20% of the operation area.

3.8 Evaluation Technique

This system is evaluated by simulations in OPNET 10.5A. There are several reasons why simulation should be used instead of analytical models or direct measurement. The most obvious reason is that general analytical models do not exist for mobile ad hoc networks, so this is not possible without first creating the analytical model. Additionally, there are not many networks available for direct measurements since MANETs are a new technology. It would be difficult to obtain the materials necessary to set up a MANET large enough to conduct these experiments. Furthermore, it would be difficult to make them follow a specific mobility pattern. Simulations provide a controllable environment which gives repeatable results.

OPNET 10.5A includes an implementation of AODV. The implementation is verified by running simulations using the random waypoint mobility model, which is also implemented in OPNET, and comparing the results to those in [DPR00]. Packet delivery percent, the percent of successfully delivered packets, is used as a basis of comparison.

Results are validated based on expert intuition. Trends should be similar in common network performance metrics such as end-to-end delay. For example, ETE delay is expected to be higher with a heavy traffic load than with a light traffic load. Therefore, simulations with 30 sources should have higher ETE delay than those with 20 sources.

3.9 Experimental Design

A full factorial design is used for this experiment. Each of the 4 factors has 2 levels, so the full factorial design requires 2*2*2*2=16 experiments. Five replications are expected to provide a sufficient statistical basis for analysis. Thus, 80 total experiments are required.

Nodes are initially randomly distributed at the intersection points of the Voronoi diagram. However, nodes are not likely to be in this position after they have been moving for a period of time according to the mobility models. Thus, simulations must be run for long enough to eliminate the effects of initial conditions. The length of the simulations varies according to the time required for each simulation to reach steady state. To eliminate the effects of transient data, only the last 2000 seconds of each simulation is used.

Variance is expected to be small because the initial node positions in different replications should not cause very different results after the initialization period. Similar to [CBD02], 95% confidence intervals are used. The random seed is changed before each simulation run to ensure experiments are independent.

3.10 Summary

MANETs are a relatively new technology that can be used in networks without any supporting infrastructure. As the price of mobile devices continues to drop, MANETs will become a cost effective solution to the need for networks in many situations. At one end of the spectrum, they can be used to share files in meetings or connect to play games among friends. They can also be used to quickly set up a network during disaster recovery or in military combat situations. Before MANETs can be used in these situations, their performance must be tested.

This chapter defines a methodology to determine the effect of mobility on a common MANET routing protocol. The system, system services, and workload are explained in detail. Performance metrics, parameters, and factors are also defined. Finally, the experimental design is explained.

IV. Analysis and Results

This chapter contains the results of this research and an analysis of those results. The first section contains the verification of the AODV implementation in OPNET. The following sections contain the results of the simulations and include an analysis of throughput, goodput, ETE delay, node pair goodput, and node pair ETE delay.

4.1 Verification of AODV Implementation

To verify correct behavior of the OPNET implementation of AODV, simulation results are compared to the results given in [DPR00]. All simulations use the random waypoint model. The pause times used are 0, 25, 75, 125, 300, 600, and 900 seconds. Other important simulation settings are shown in Table 4.1.

Table 4.1: Verification simulation settings

Parameter	Setting
Simulation Area/ Number of Nodes	1500 m by 300 m/50 nodes
Number of Source Nodes	40
Node Speed	Uniformly distributed 0-20 m/sec
Packet Size	512 bytes
Simulation Time	900 seconds

The fraction of successfully delivered packets is used to compare results. The data points for the [DPR00] results shown in Figure 4.1 are approximate, as they were read from a graph with limited resolution. The results of the OPNET simulations and the results from [DPR00] follow a similar trend. That is, the packet delivery percent decreases initially when the pause time changes from 0 to 25 seconds, and increases as pause time gets larger than 125 seconds. However, the packet delivery fraction from the verification simulations is statistically higher than [DPR00] at a 95% confidence level.

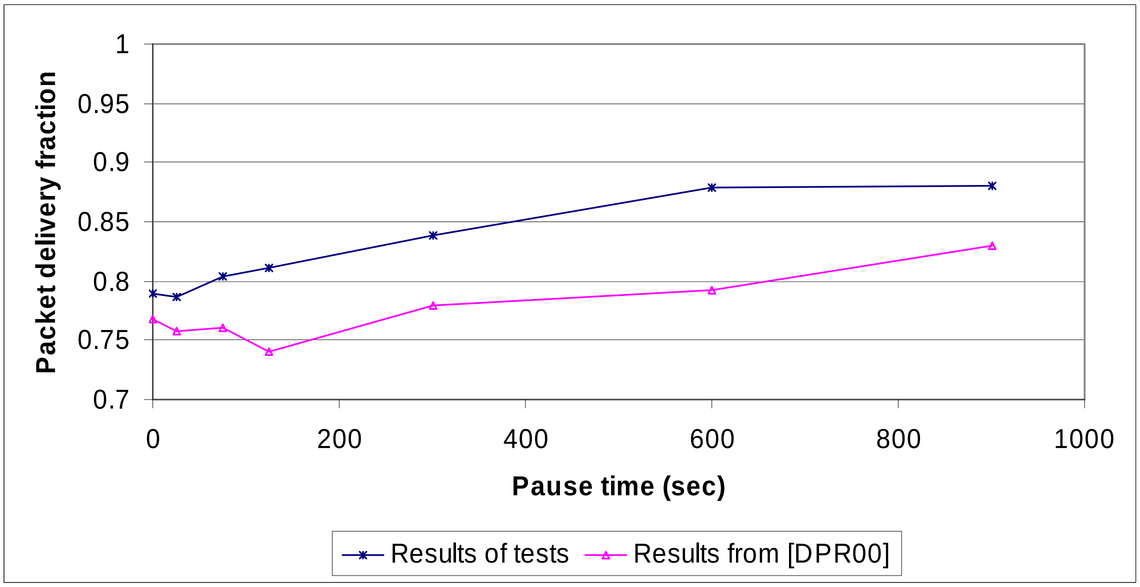


Figure 4.1: Results to Verify OPNET AODV implementation

The simulation model from [DPR00] was created for [BMJ98]. This implementation is based on a 1997 IETF Internet draft [Per97]. However, the authors of [BMJ98] did not implement AODV exactly as the internet draft explains it. Instead, they implemented AODV-LL (link layer), without the AODV hello messages. Thus, all link breakage in AODV-LL can only be detected when a node attempts to send a packet over the link. AODV hello messages allow nodes to detect link breakages before a packet is sent. The current OPNET implementation is based on a more recent description of AODV [PBD03].

Some AODV settings differed between the [BMJ98] implementation and the default OPNET implementation. The active route time for the [BMJ98] implementation is 300 seconds, while the OPNET implementation uses a 3 second active route timeout.

The long active route time used by [BMJ98] will most likely result in a large number of stale routes. A packet sent using a stale route must be resent after a new route is discovered. If route discovery takes a long time, the packet may be dropped. The OPNET implementation also allows more route request retries. Although [PBD03] calls for 2 route request retries, the OPNET implementation uses 5 while only 3 are used in [BMJ98].

4.2 Throughput Analysis

Figure 4.2 shows throughput for the obstacle mobility model. Throughput is normalized to the line speed of 11 Mbps, and the graph shows the 95% confidence interval of the mean. As seen in Figure 4.2, when nodes are traveling according to the obstacle mobility model throughput is greater when obstacles are present than when there are no obstacles. This is explained by the extra routing traffic required.

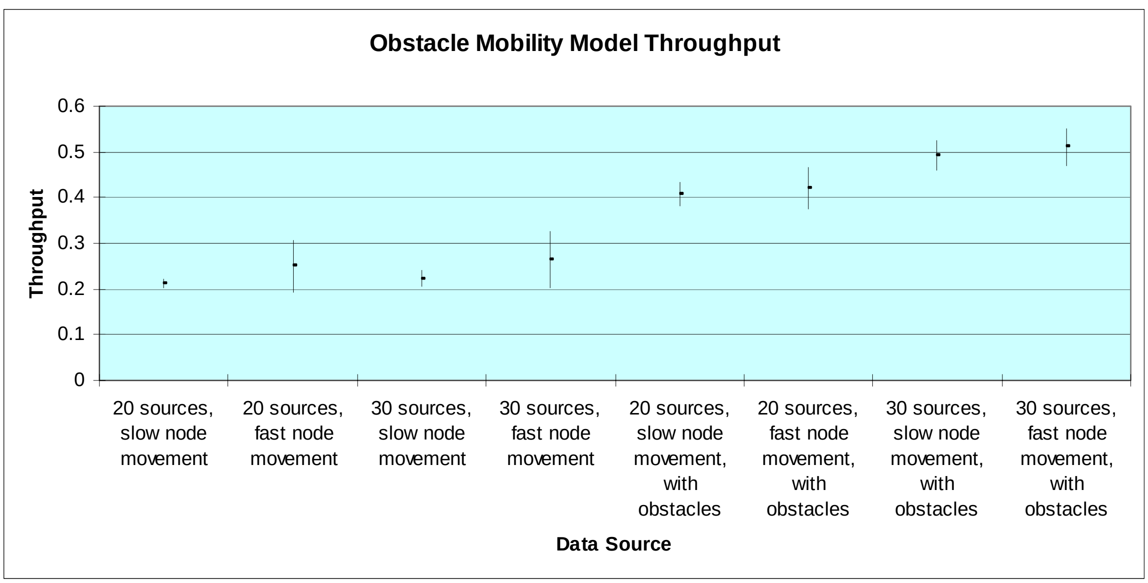


Figure 4.2: Obstacle Mobility Model Throughput

Without obstacles each node can transmit to any other node within 250 meters. Conversely, when obstacles are present a node may not be able to communicate directly with a node that is much closer than 250 meters if an obstacle lies between them. In this situation the sender must route traffic through another node to get around the obstacle. This situation is depicted in Figure 4.3.

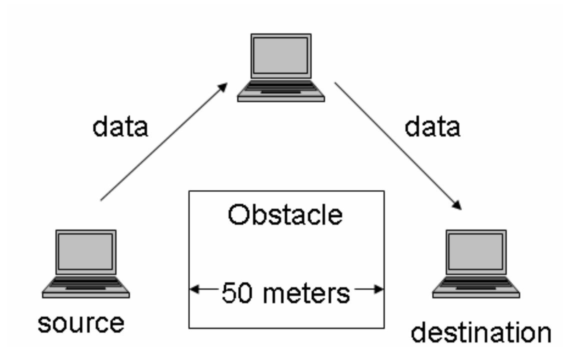


Figure 4.3: Routing traffic around an obstacle

When obstacles are not present, throughput is not affected by the number of source nodes or by the node speed. However, when obstacles are present, networks with 30 source nodes have a significantly higher throughput than networks with 20 source nodes regardless of node speed. Since the confidence intervals for 20 source nodes with fast node movement and 30 source nodes with slow node movement overlap, a *t*-test is used to determine that the 30 source networks have higher throughput.

In most cases when RPGM is used, throughput is lower when obstacles are present (Figure 4.4). Seventy-five percent of the traffic generated by the data sources is sent to a node within the same group, so the obstacles do not affect this portion of traffic. The remaining 25% of source data is sent outside the group and must be routed around obstacles. Due to the group mobility pattern, nodes are concentrated in several areas and may not be in a position to route traffic around an obstacle. When a route cannot be found the packets will be dropped. This is less likely to occur when nodes travel individually because they will be dispersed throughout the network area.

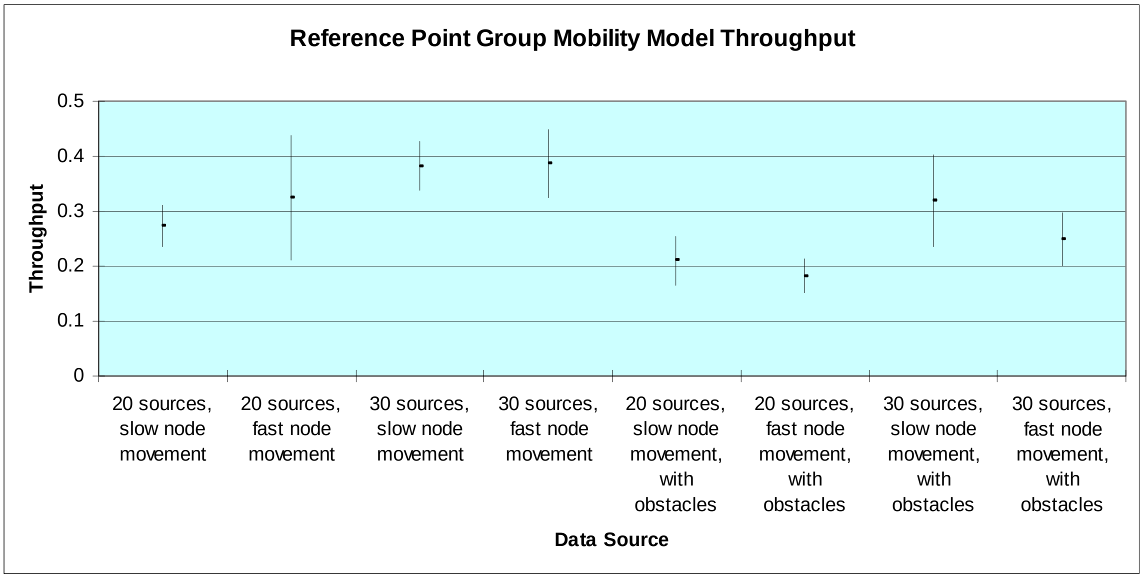


Figure 4.4: Reference Point Group Mobility Throughput

The analysis of variance in Table 4.2 shows that the majority of variation is due to the factors in the test, not error. Specifically, mobility model, number of sources, obstacles, and the interaction between mobility model and number of sources explain most of the variation. All other factor interactions explain less than 5% of variation. The analysis of variance tables for the other performance metrics will not be included in this chapter, but they are included in Appendices B, C, D, and E.

Table 4.2: Throughput Analysis of Variance

Source	Sum of Squares	Percent of Variation	Degrees of Freedom	F Ratio	Prob > F
C. Total	2.125E+13	1.00000	15	.	
Model	2.125E+13	0.999995	14	9480.343	0.0080
Error	1.601E+08	0.000008	1		
Mobility	1.725E+12	0.0812	1	10774.69	0.0061
NumSources	1.907E+12	0.0897	1	11908.52	0.0058
Obstacles	2.463E+12	0.1159	1	15383.08	0.0051
Speed	4.022E+10	0.0019	1	251.23	0.0401
Mobility*NumSources	1.381E+13	0.6499	1	86263.07	0.0022
Mobility*Obstacles	1.885E+11	0.0089	1	1177.26	0.0185
Mobility*Speed	1.902E+11	0.0089	1	1187.72	0.0185
NumSources*Obstacles	1.894E+11	0.0089	1	1182.97	0.0185
NumSources*Speed	3.231E+11	0.0152	1	2018.31	0.0142
Obstacles*Speed	5.656E+10	0.0027	1	353.24	0.0338
Mobility*NumSources*Obstacles	1.741E+11	0.0082	1	1087.49	0.0193
Mobility*NumSources*Speed	1.003E+11	0.0047	1	626.31	0.0254
Mobility*Obstacles*Speed	8.109E+10	0.0038	1	506.49	0.0283
NumSources*Obstacles*Speed	7.069E+08	0.0000	1	4.42	0.2828

4.3 Goodput Ratio Analysis

Goodput measures the ratio of data bits successfully received relative to all bits transmitted. It is a higher better metric. Figure 4.5 clearly shows that when nodes follow the obstacle mobility model goodput is significantly higher without obstacles. This is due to the extra routing information that is transmitted in order to successfully route packets around obstacles. Furthermore, when following the obstacle mobility model without obstacles, goodput ratio is significantly higher with 30 source nodes regardless of node speed.

When obstacles are present there is not a single factor that always results in a higher goodput ratio. The network with 30 sources and slow node movement achieves a higher goodput ratio than both networks that have fast node movement, but the 20 source network with slow node movement does not achieve a higher goodput ratio than the other networks.

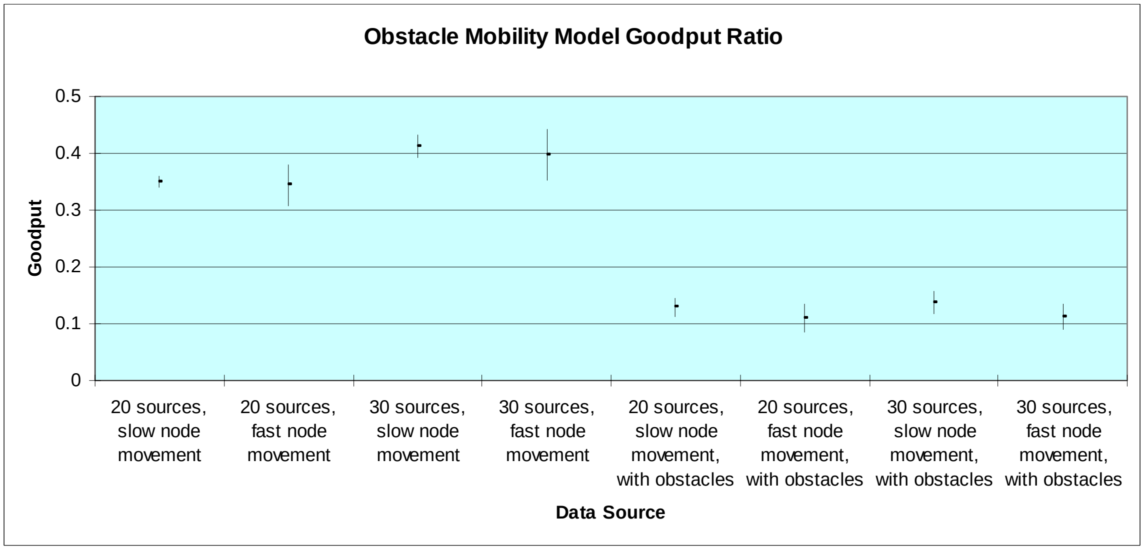


Figure 4.5: Obstacle Mobility Model Goodput Ratio

Networks with nodes following the reference point group mobility model achieve higher goodput than networks with nodes following the obstacle mobility model, except when there are 30 source nodes and no obstacles, as seen in Figures 4.5 and 4.6. In most cases reference point group mobility results in a higher goodput ratio because most traffic is sent to nodes that are very close to each other. Only 25% of the traffic generated is sent outside the group. In some cases, obstacle model simulations without obstacles and 30 sources results in a goodput ratio similar to that achieved by the RPGM model. This occurs because of the extra source traffic generated by 30 sources.

As seen in Figure 4.6, when mobile nodes move in groups according to RPGM goodput ratio is very similar, and comes close to achieving 50% of traffic sent being data. There is a large amount of variance when there are 30 source nodes and slow node movement.

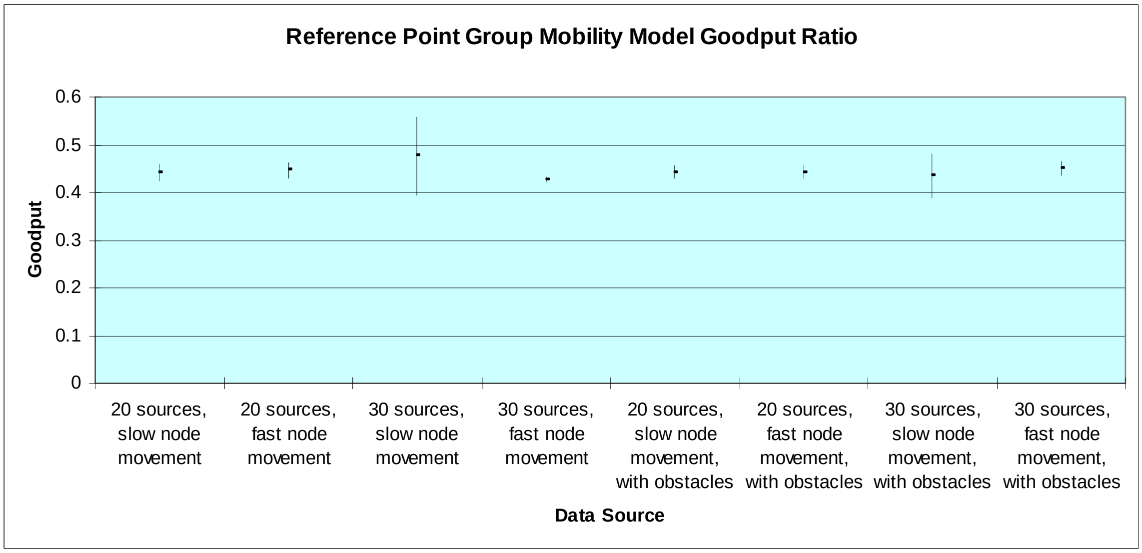


Figure 4.6: Reference Point Group Mobility Model Goodput Ratio

The goodput ratio analysis of variance shows that 99.89% of variation in goodput ratio is due to test factors (Table B.5). The largest amount of variation is explained by the mobility model. The results in Figures 4.5 and 4.6 support this. The number of sources and the interaction between the mobility model and number of sources also account for a large portion of variation.

4.4 End-to-End Delay Analysis

ETE delay measures the time it takes to transmit information. The significance of ETE delay changes with the time sensitivity of the information being transmitted. As seen in Figure 4.7, ETE delay for the obstacle mobility model simulations without obstacles is not affected by the number of sources or the node speed.

As seen in Figure 4.7 and 4.8, ETE delay is much lower when obstacles are not present. This is because of the extra time it takes to transmit routing information in order to send packets around obstacles. The ETE delay with obstacles would be lower if obstacles did not completely block traffic.

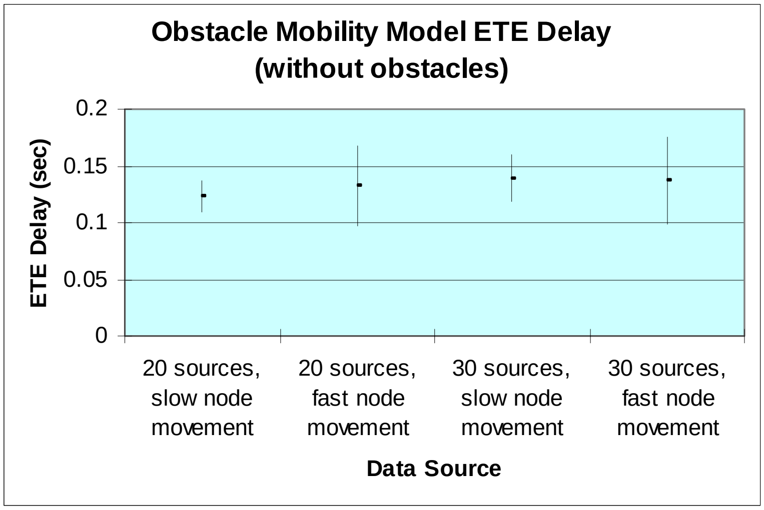


Figure 4.7: Obstacle Mobility Model ETE Delay (without obstacles)

Figure 4.8 shows the ETE delay for the obstacle mobility model with obstacles. With obstacles present ETE delay is the same most of the time, however, 20 source nodes with fast node movement results in a lower ETE delay than 30 source nodes with slow movement. Since nodes are moving slower, they remain in obstacles for a longer period of time when they are moving slower. Thus, traffic that is waiting to be sent to a node inside an obstacle must wait longer.

Figure 4.8 also shows a large confidence interval for the simulation with 30 sources and fast node movement. This is caused by one data point that is drastically higher than the other replications. The second replication of this simulation achieved an ETE delay that is nearly three times greater than the next highest ETE delay. Due to the randomness of the simulations an exact cause cannot be determined. It is possible that the paths the node followed combined with the random packet destinations caused a high number of packets to wait for a node to pass through an obstacle before being sent.

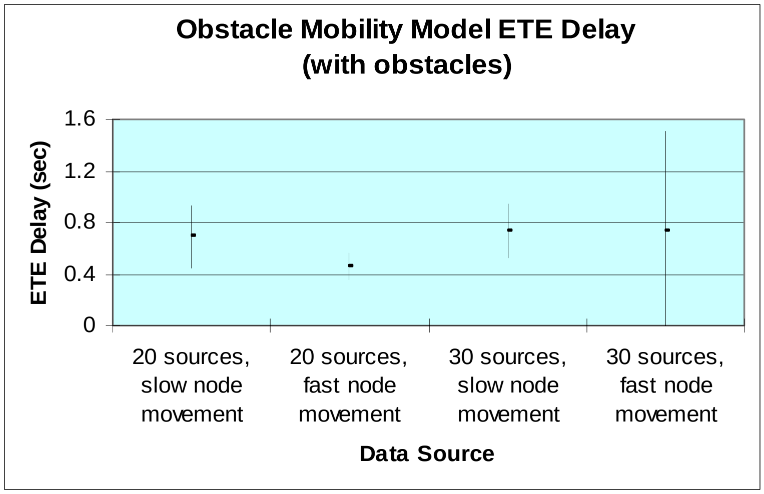


Figure 4.8: Obstacle Mobility Model ETE Delay (with obstacles)

As seen in Figure 4.9, RPGM achieves the lower ETE delay than the obstacle mobility model. Since each member of a group stays within 5 meters of the group leader, intra-group traffic will only have one hop. Since each source sends 75% of packets to one of the other four group members, these routes should be used often enough to remain in the route table. In the cases where the routes time out, it would not take long to send a route request and receive a route reply. The proximity of the nodes within a group also keeps propagation delay very low. Figure 4.9 also shows that in most cases fast node movement results in a lower ETE delay than slow node movement.

As with the previous performance metrics, the analysis of variance in Table C.5 shows that over 99% of variation is due to test factors. Mobility model and obstacles explain a large amount of variation, as does the interaction between mobility model and obstacles.

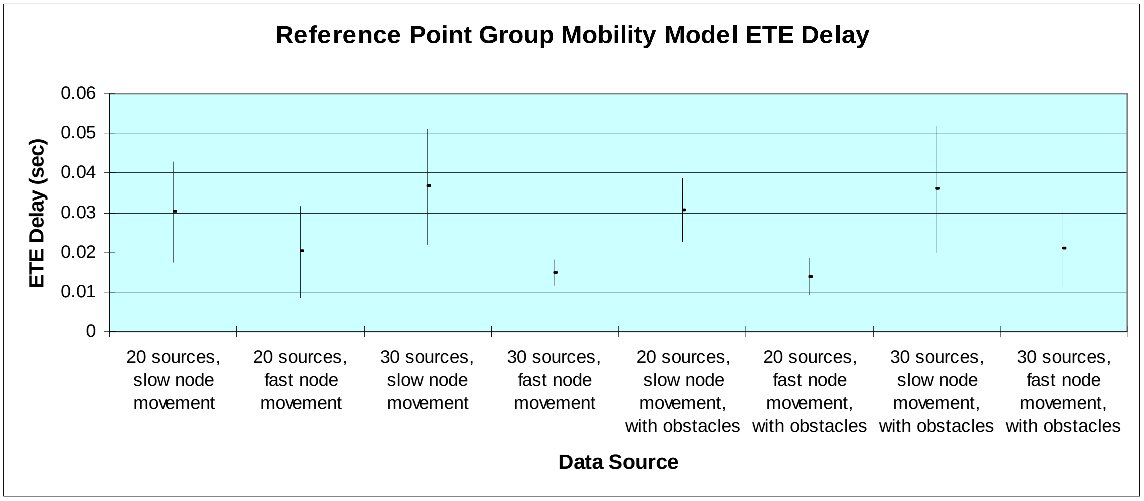


Figure 4.9: Reference Point Group Mobility Model ETE Delay

4.5 Node Pair Packet Delivery Rate Analysis

To measure node pair packet delivery rate one source is assigned to send all of its packets to a particular destination. Node pair packet delivery rate measures the ratio of packets that reach the destination node. Figure 4.10 shows node pair packet delivery rate for the obstacle mobility model. The *t*-test is performed to test the significance in the cases where the 95% confidence intervals overlap. Node pair packet delivery rate is significantly higher when obstacles are not present.

It is not surprising that obstacles result in a lower packet delivery rate. Obstacles may cause several situations that would prevent transmission between the source and destination. If the source or destination is inside an obstacle while the other is not or if they are both in different obstacles, they will not be able to transmit. Also, if they are on opposite sides of an obstacle and there is not a path to route around the obstacle, then the source and destination cannot transmit.

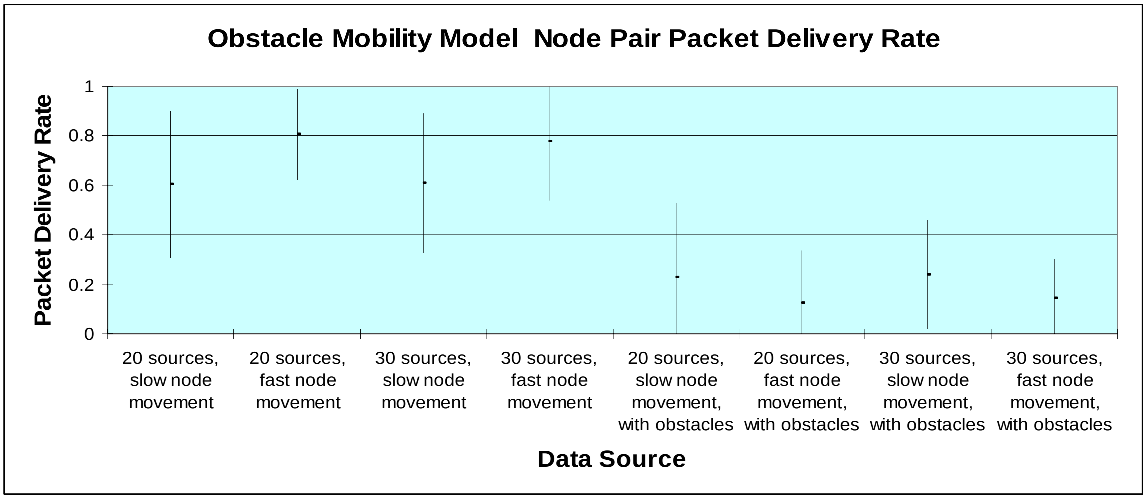


Figure 4.10: Obstacle Mobility Model Node Pair Packet Delivery Rate

As seen in Figure 4.11, using RPGM sometimes results in a node pair packet delivery rate of zero. Since nodes travel in groups of five, there are only ten groups in the simulation area. Also, the diameter of a group is limited to 10 meters, since a node must stay within 5 meters of the group leader. This will limit the coverage of the simulation area, and can cause separations in the network. This becomes a bigger problem when obstacles are present because it is likely that groups will not be able to route traffic around an obstacle if the source and destination nodes are on opposing sides.

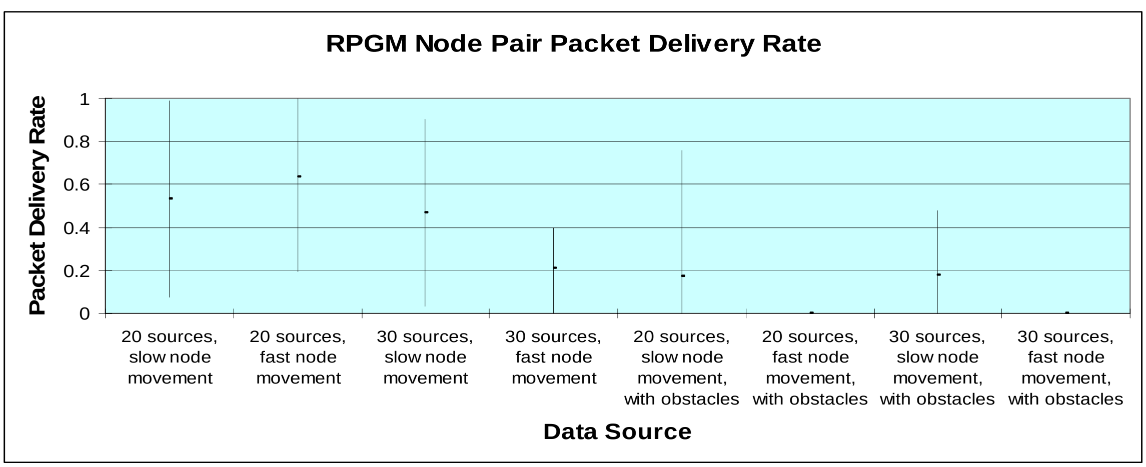


Figure 4.11: RPGM Node Pair Packet Delivery Rate

Until now, the source and destination nodes used for node pair packet delivery rate are in different groups. When the source and destination nodes belong to the same group the node pair packet delivery rate is not statistically different than 1. This is expected because the source and destination are always within 10 meters of one another, so a route is always available. Additionally, there is not enough traffic being generated for congestion to interfere with packet transmission. The data for this scenario is in Table D.4.

The analysis of variance for the inter-group and intra-group node pairs show that over 99% of variation is explained by test factors (Table D.5). In both situations mobility model and the number of sources explain a large percent of variation. For the inter-group node pair the number of sources explains 72% of the variation, and mobility model explains 10%. For the intra-group node pair mobility model explains 68%, and number of sources explains 15%. The interaction between mobility model and number of sources contributes to variation for the intra-group node pair.

4.6 Node Pair ETE Delay Analysis

When using the obstacle mobility model, node pair ETE delay is not affected by obstacles, node speed, or the number of sources (Figure 4.12). Node pair ETE delay is less than the ETE delay experienced by the entire MANET. In order to collect node pair statistics one source node sends all traffic to a single destination while the other source nodes do not generate traffic for this destination. Since this source will send 4 packets per second to this destination, the route will not expire. A new route will only have to be discovered when the old route becomes invalid.

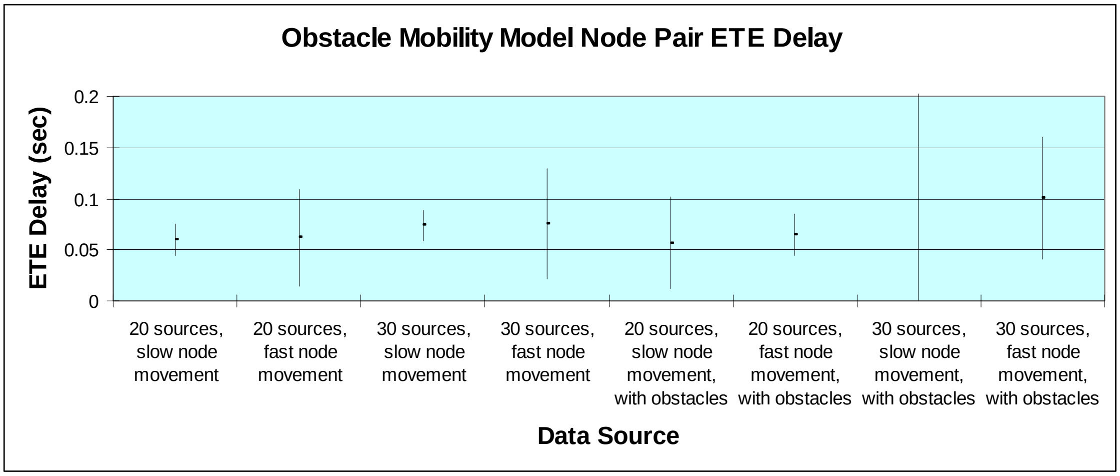


Figure 4.12: Obstacle Mobility Model Node Pair ETE Delay

Comparing Figure 4.12 and Figure 4.13 shows that in most cases node pair ETE delay is lower with RPGM than with the obstacle mobility model when obstacles are present. It is not possible to calculate node pair ETE delay for RPGM with obstacles and fast node speed because the packet delivery rate is zero and ETE delay cannot be calculated if no packets are received.

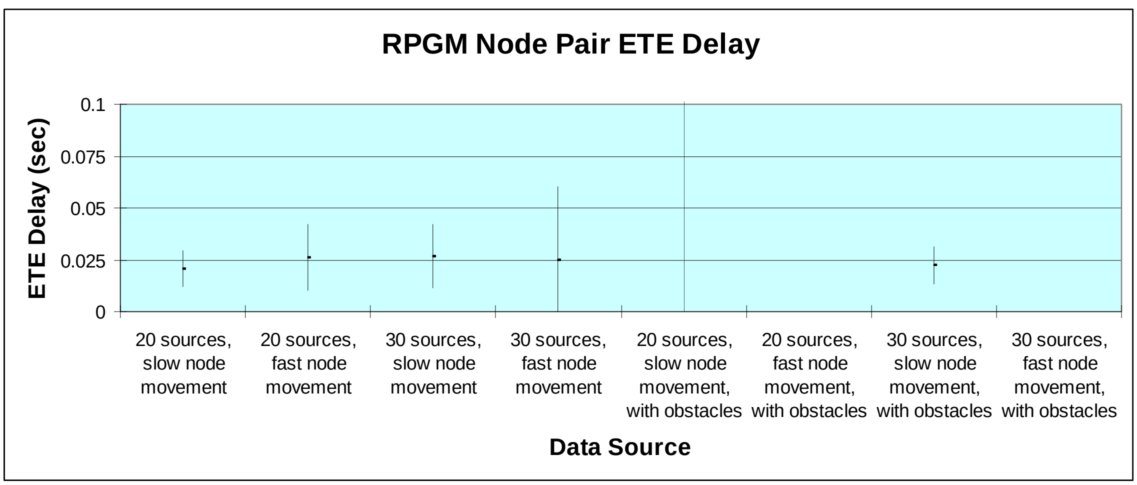


Figure 4.13: RPGM Node Pair ETE Delay

Figure 4.14 shows node pair ETE delay for RPGM with the source and destination in the same group. In this case, the source and destination are always within

10 meters of each other, as each node can only be 5 meters away from the group center. When the group enters an obstacle, either the source or destination will enter before the other and they will not be able to communicate for a brief period. However, due to group mobility the other node will soon enter and communication can resume.

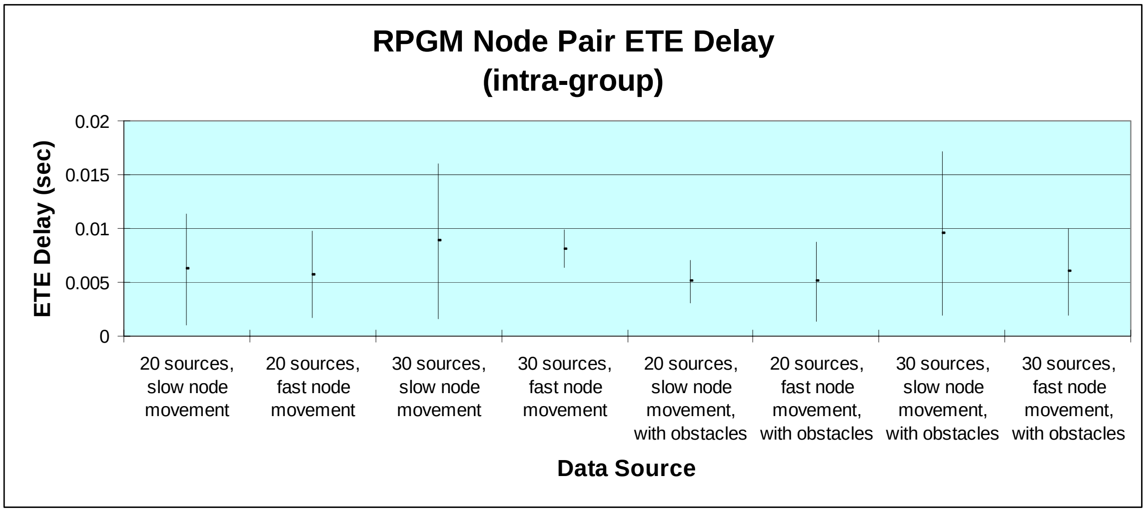


Figure 4.14: RPGM Node Pair ETE Delay (intra-group)

Analysis of variance cannot be performed on the inter-group data because data is not available for fast node movement with obstacles. For the intra-group node pair the test factors explain 97% of variation. The largest percent of variation is due to mobility model. The other factors and interactions between factors explain between 3 and 10 percent of variation.

4.7 Summary

This chapter describes the verification of the OPNET AODV implementation. The results are compared to [DPR00], and discrepancies are explained. Next, the results of performance metrics are presented and explained. An analysis of variance shows that all test factors are significant for these performance metrics.

V. Conclusions and Recommendations

This chapter provides a summary of the research problem, the research conclusions and significance, and recommendations for future research.

5.1 Problem Summary

MANETs cannot use the same routing protocols as wired networks or wireless local area networks due to limitations of the mobile nodes and the dynamic nature of the network. Several routing protocols have been designed specifically for use in MANETs. It is important to test routing protocols in the situation in which it will be used. Since node mobility is known to affect routing protocol performance, tests should use the mobility model that most closely represents the expected movement of mobile nodes. Other factors such as obstacles in the network area, node speed, and the number of sources should also be considered.

5.2 Conclusions of Research

The performance of AODV is dependent on most of the factors used in this research. Node speed is the only factor that did not affect results. The mobility model affected the results of throughput, goodput ratio, ETE delay, node pair goodput ratio, and node pair ETE delay. Depending on the performance metric, the mobility model explains from 8 to 68 percent of variation. It had the greatest effect on node pair packet delivery rate when the source and destination belong to the same group, and affected throughput the least.

The number of source nodes affected all performance metrics except ETE delay. ETE delay was not affected by the number of source nodes because changing from 20 to 30 source nodes did not stress the line speed of 11 Mbps. In order to stress the line speed the packet size or the number of packets sent by each source must be increased.

Obstacles in the simulation area affect throughput, ETE delay, and node pair ETE delay due to the extra time and routing information required to route traffic around obstacles. Obstacles explain between 5 and 24 percent of variation for the performance metrics listed.

5.3 Significance of Research

This research is the first MANET study to measure performance metrics for a particular node pair. In many situations individuals are not concerned with the average throughput, goodput ratio, and ETE delay that the network achieves. However, individuals are concerned with the amount of traffic that they can transmit/receive and how long it takes. Node pair performance metrics provide this information.

This research is also the first to study the effect of obstacles when using reference point group mobility model. Previously the effect of obstacles has only been studied with the obstacle mobility and random waypoint models. Obstacles affect node movement as well as data transmission.

5.4 Recommendations for Future Research

In this research obstacles completely block signal propagation. This is not realistic because signal propagation depends on the size and composition of the obstacles.

Completely blocking signal propagation isolates nodes that enter obstacles from the rest of the network. Allowing signal propagation through buildings should show a performance improvement.

As the study of MANETs progress and new routing protocols emerge they should be tested. The factors and performance metrics in this study consider many aspects that will affect routing protocol performance. Currently, there is an internet-draft for dynamic source routing and requests for comments for ad hoc on demand distance vector routing and optimized link state routing. Future works should also consider different mobility models.

Appendix A. Throughput Results

Table A.1: Throughput Data

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	2402325	3074790	4653666	5352524
		2374143	2373315	4810217	4826457
		2582316	3000522	4737434	4208620
		2455831	3584517	4345811	4878706
		2436534	2356516	4980000	5070697
	30sources	2446978	3318915	5874319	6506183
		2433007	2534164	5866187	5586059
		2810460	3162781	5795600	5613961
		2616167	3787757	5134978	5726897
		2568868	2375454	5673040	6025329
RPGM	20sources	3452904	2949211	2679539	1970438
		2753381	2963199	1858538	2113617
		3246369	4846250	2940684	2289569
		3568166	2707011	2316367	2457203
		2979971	4454277	2316967	1688031
	30sources	4293054	4437075	4763714	2520911
		3939758	5226944	2739689	3223088
		4559191	3844630	4134985	3496403
		5059631	4777651	3333096	2477268
		4201731	3986509	3402575	2646453

Table A.2: Throughput Means

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	2450230	2877932	4705426	4867401
	30sources	2575096	3035814	5668825	5891686
RPGM	20sources	3136972	3742684	2422419	2103772
	30sources	4410673	4454562	3674812	2872825

Table A.3: Throughput Standard Deviation

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	80233.81	519508.5	234200.2	422039.5
	30sources	153072.9	580821	309136.6	385085
RPGM	20sources	351039.9	1065276	410803.6	295867.1
	30sources	424987.2	568409.3	784666.6	459098.9

Table A.4: Throughput 95% Confidence Intervals

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	2350622	2232980	4414674	4343453
		2549837	3522884	4996177	5391348
	30sources	2385061	2314745	5285043	5413616
		2765131	3756883	6052607	6369755
RPGM	20sources	2701168	2420182	1912421	1736463
		3572775	5065187	2932417	2471080
	30sources	3883066	3748902	2700676	2302869
		4938279	5160222	4648948	3442780

Table A.5: Throughput Analysis of Variance (ANOVA)

Source	Sum of Squares	Percent of Variation	Degrees of Freedom	F Ratio	Prob > F
C. Total	2.125E+13	1.00000	15	.	
Model	2.125E+13	0.999995	14	9480.343	0.0080
Error	1.601E+08	0.000008	1		
Mobility	1.725E+12	0.0812	1	10774.69	0.0061
NumSources	1.907E+12	0.0897	1	11908.52	0.0058
Obstacles	2.463E+12	0.1159	1	15383.08	0.0051
Speed	4.022E+10	0.0019	1	251.23	0.0401
Mobility*NumSources	1.381E+13	0.6499	1	86263.07	0.0022
Mobility*Obstacles	1.885E+11	0.0089	1	1177.26	0.0185
Mobility*Speed	1.902E+11	0.0089	1	1187.72	0.0185
NumSources*Obstacles	1.894E+11	0.0089	1	1182.97	0.0185
NumSources*Speed	3.231E+11	0.0152	1	2018.31	0.0142
Obstacles*Speed	5.656E+10	0.0027	1	353.24	0.0338
Mobility*NumSources*Obstacles	1.741E+11	0.0082	1	1087.49	0.0193
Mobility*NumSources*Speed	1.003E+11	0.0047	1	626.31	0.0254
Mobility*Obstacles*Speed	8.109E+10	0.0038	1	506.49	0.0283
NumSources*Obstacles*Speed	7.069E+08	0.0000	1	4.42	0.2828

Appendix B. Goodput Results

Table B.1: Goodput Data

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.349596	0.334345	0.123965	0.108389
		0.35904	0.369413	0.113261	0.12526
		0.344117	0.339238	0.147431	0.097176
		0.342257	0.303444	0.134937	0.086461
		0.358998	0.37596	0.124402	0.135429
	30sources	0.416592	0.388412	0.128182	0.116725
		0.429212	0.424506	0.120728	0.11331
		0.406484	0.381855	0.163346	0.102882
		0.388812	0.353257	0.14164	0.092231
		0.422757	0.44429	0.135504	0.141482
RPGM	20sources	0.560974	0.473668	0.43039	0.449295
		0.428002	0.436799	0.455533	0.442382
		0.457769	0.461793	0.439284	0.430092
		0.430486	0.436576	0.439136	0.434094
		0.450726	0.450468	0.450219	0.458101
	30sources	0.592331	0.426396	0.366947	0.460661
		0.437206	0.418781	0.458496	0.446793
		0.462079	0.428154	0.44664	0.431663
		0.431984	0.431965	0.44503	0.45804
		0.462495	0.430709	0.455274	0.458738

Table B.2: Goodput Means

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.350802	0.34448	0.128799	0.110543
	30sources	0.412772	0.398464	0.13788	0.113326
RPGM	20sources	0.441746	0.446409	0.442913	0.442793
	30sources	0.477219	0.427201	0.434478	0.451179

Table B.3: Goodput Standard Deviation

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.007972	0.029269	0.012932	0.019995
	30sources	0.015797	0.036051	0.016252	0.018428
RPGM	20sources	0.014754	0.012141	0.009961	0.011333
	30sources	0.065848	0.005183	0.038174	0.012189

Table B.4: Goodput 95% Confidence Intervals

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.340905	0.308143	0.112745	0.08572
		0.360698	0.380817	0.144854	0.135366
	30sources	0.39316	0.353708	0.117703	0.090448
		0.432383	0.44322	0.158057	0.136204
RPGM	20sources	0.423429	0.431337	0.430546	0.428723
		0.460063	0.461481	0.455279	0.456862
	30sources	0.395471	0.420767	0.387086	0.436047
		0.558967	0.433636	0.481869	0.466311

Table B.5: Goodput ANOVA

Source	Sum of Squares	Percent of Variation	Degrees of Freedom	F Ratio	Prob > F
C. Total	0.2880	1.00000	15		
Model	0.2877	0.99894	14	0.288	0.02055
Error	0.0003	0.00106	1		
Mobility	0.1534	0.5328	1	503.71	0.0283
NumSources	0.0672	0.2335	1	220.71	0.0428
Obstacles	0.0013	0.0045	1	4.26	0.2873
Speed	0.0005	0.0018	1	1.74	0.4125
Mobility*NumSources	0.0618	0.2148	1	203.03	0.0446
Mobility*Obstacles	0.0008	0.0027	1	2.56	0.3559
Mobility*Speed	0.0001	0.0003	1	0.25	0.7066
NumSources*Obstacles	0.0009	0.0031	1	2.97	0.3345
NumSources*Speed	0.0001	0.0003	1	0.32	0.6704
Obstacles*Speed	0.0002	0.0006	1	0.56	0.5916
Mobility*NumSources*Obstacles	0.0005	0.0017	1	1.58	0.4278
Mobility*NumSources*Speed	0.0004	0.0015	1	1.45	0.4410
Mobility*Obstacles*Speed	0.0000	0.0001	1	0.11	0.7927
NumSources*Obstacles*Speed	0.0003	0.0012	1	1.10	0.4850

Appendix C. ETE Delay Results

Table C.1: ETE Delay Data

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.129309	0.183218	0.98971	0.555439
		0.102894	0.121397	0.626266	0.393797
		0.130133	0.121243	0.52434	0.414039
		0.124338	0.116739	0.528135	0.557705
		0.128966	0.118021	0.776977	0.402084
	30sources	0.138918	0.192693	0.88916	0.633147
		0.116403	0.1293	0.606847	1.830731
		0.129303	0.117267	0.597446	0.470135
		0.150737	0.122568	0.622324	0.462008
		0.159623	0.124315	0.952392	0.286809
RPGM	20sources	0.04179	0.030588	0.03614	0.010989
		0.026584	0.011905	0.021746	0.019392
		0.020868	0.027094	0.028822	0.009927
		0.028462	0.01229	0.028566	0.013247
		0.04465	0.029032	0.037675	0.015784
	30sources	0.045432	0.018149	0.048873	0.012254
		0.030741	0.015978	0.021339	0.02603
		0.021885	0.013414	0.028752	0.01663
		0.033821	0.011403	0.030468	0.018498
		0.051122	0.015598	0.050133	0.031201

Table C.2: ETE Delay Means

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.123128	0.132123	0.689086	0.464613
	30sources	0.138997	0.137228	0.733634	0.736566
RPGM	20sources	0.030141	0.02008	0.03059	0.013868
	30sources	0.0366	0.014908	0.035913	0.020922

Table C.3: ETE Delay Standard Deviation

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.011535	0.028634	0.196909	0.084259
	30sources	0.017086	0.031302	0.172522	0.623807
RPGM	20sources	0.010197	0.009253	0.006451	0.003821
	30sources	0.011699	0.002581	0.012879	0.007602

Table C.4: ETE Delay 95% Confidence Intervals

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.108808	0.096575	0.444631	0.360009
		0.137448	0.167672	0.933541	0.569217
	30sources	0.117785	0.098368	0.519454	0
		0.160208	0.176089	0.947814	1.511001
RPGM	20sources	0.017481	0.008593	0.022581	0.009125
		0.042801	0.031567	0.038598	0.018611
	30sources	0.022076	0.011704	0.019924	0.011485
		0.051124	0.018113	0.051902	0.03036

Table C.5: ETE Delay ANOVA

Source	Sum of Squares	Percent of Variation	Degrees of Freedom	F Ratio	Prob > F
C. Total	1.1430	1.0000	15		
Model	1.1399	0.99724	14	25.7766	0.15331
Error	0.0032	0.00276	1		
Mobility	0.5448	0.4766	1	172.47	0.0484
NumSources	0.0077	0.0067	1	2.44	0.3625
Obstacles	0.2735	0.2393	1	86.60	0.0682
Speed	0.0048	0.0042	1	1.53	0.4331
Mobility*NumSources	0.0066	0.0057	1	2.07	0.3863
Mobility*Obstacles	0.2738	0.2395	1	86.67	0.0681
Mobility*Speed	0.0014	0.0012	1	0.45	0.6238
NumSources*Obstacles	0.0059	0.0051	1	1.86	0.4028
NumSources*Speed	0.0027	0.0023	1	0.85	0.5266
Obstacles*Speed	0.0033	0.0029	1	1.04	0.4945
Mobility*NumSources*Obstacles	0.0051	0.0044	1	1.60	0.4258
Mobility*NumSources*Speed	0.0032	0.0028	1	1.02	0.4976
Mobility*Obstacles*Speed	0.0033	0.0029	1	1.04	0.4944
NumSources*Obstacles*Speed	0.0040	0.0035	1	1.25	0.4643

Appendix D. Node Pair Packet Delivery Rate Results

Table D.1: Node Pair Packet Delivery Rate Data

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.71625	0.783375	0.624375	0
		0.607875	0.9115	0.135375	0.156782
		0.863375	0.719375	0.285625	0
		0.22125	0.62375	0.004625	0.06006
		0.613125	0.99675	0.097625	0.410285
	30sources	0.690875	0.732375	0.48425	0.002628
		0.615	0.95	0.146875	0.193193
		0.84475	0.635625	0.329875	0
		0.231875	0.56675	0.020125	0.249499
		0.65925	0.9895	0.209875	0.262012
RPGM	20sources	0.973	0.12025	0.154375	0
		0	0.999625	0.008	0
		0.592125	0.921625	0.460875	0
		0.717625	0.510875	0.024125	0
		0.3705	0.60925	0.200125	0
	30sources	0.962875	0.042625	0.031375	0
		0	0	0	0
		0.54425	0	0.57025	0
		0.51225	1	0.03625	0
		0.322125	0	0.260875	0

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.9545	1	0.973625	1
		1	1	0.994625	0.987625
		1	1	0.991375	0.99425
		0.999875	1	0.97875	1
		1	1	1	0.9785
	30sources	0.999375	1	0.97375	1
		1	0.99975	0.995125	0.987875
		1	0.99975	0.989375	0.99425
		0.999875	1	0.980125	0.996375
		0.999375	1	1	0.978375

Table D.2: Node Pair Packet Delivery Rate Means

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.604375	0.80695	0.229525	0.125425
	30sources	0.60835	0.77485	0.2382	0.141466
RPGM	20sources	0.53065	0.632325	0.1695	0
	30sources	0.4683	0.208525	0.17975	0

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.990875	1	0.987675	0.992075
	30sources	0.999725	0.9999	0.987675	0.991375

Table D.3: Node Pair Packet Delivery Rate Standard Deviations

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.237945	0.148948	0.242845	0.171657
	30sources	0.227521	0.187913	0.177232	0.130544
RPGM	20sources	0.367984	0.352174	0.182539	0
	30sources	0.351061	0.442833	0.241862	0

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.020334	0	0.011079	0.009144
	30sources	0.000324	0.000137	0.010738	0.008499

Table D.4: Node Pair Packet Delivery Rate 95% Confidence Intervals

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.308975	0.622036	-0.07196	-0.08768
		0.899775	0.991864	0.531009	0.338531
	30sources	0.32589	0.541562	0.018173	-0.0206
		0.89081	1.008138	0.458227	0.303532
RPGM	20sources	0.07381	0.195113	-0.05712	0
		0.98749	1.069537	0.396116	0
	30sources	0.03247	-0.34124	-0.12051	0
		0.90413	0.758286	0.480013	0

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.965631	1	0.973921	0.980723
		1.016119	1	1.001429	1.003427
	30sources	0.999323	0.99973	0.974344	0.980824
		1.000127	1.00007	1.001006	1.001926

Table D.5: Node Pair Packet Delivery Rate ANOVA

Source	Sum of Squares	Percent of Variation	Degrees of Freedom	F Ratio	Prob > F
C. Total	1.0937	1.00000	15	.	
Model	1.0878	0.99459	14	13.126	0.213434
Error	0.0059	0.00541	1		
Mobility	0.1122	0.10262	1	18.96	0.1437
NumSources	0.7879	0.72034	1	133.09	0.0550
Obstacles	0.0144	0.01313	1	2.43	0.3634
Speed	0.0072	0.00657	1	1.21	0.4692
Mobility*NumSources	0.0203	0.01852	1	3.42	0.3155
Mobility*Obstacles	0.0140	0.01276	1	2.36	0.3675
Mobility*Speed	0.0285	0.02608	1	4.82	0.2721
NumSources*Obstacles	0.0189	0.01724	1	3.18	0.3251
NumSources*Speed	0.0362	0.03310	1	6.12	0.2446
Obstacles*Speed	0.0100	0.00916	1	1.69	0.4172
Mobility*NumSources*Obstacles	0.0123	0.01124	1	2.08	0.3862
Mobility*NumSources*Speed	0.0090	0.00820	1	1.51	0.4344
Mobility*Obstacles*Speed	0.0074	0.00672	1	1.24	0.4656
NumSources*Obstacles*Speed	0.0097	0.00890	1	1.64	0.4217

Table D.5: Node Pair Packet Delivery Rate ANOVA
Intra-group node pair

Source	Sum of Squares	Percent of Variation	Degrees of Freedom	F Ratio	Prob > F
C. Total	1.7965	1.00000	15	.	
Model	1.7965	0.99996	14	1657.862	0.019247
Error	0.0001	0.00004	1		
Mobility	1.2211	0.67970	1	15776.57	0.0051
NumSources	0.2631	0.14647	1	3399.63	0.0109
Obstacles	0.0001	0.00004	1	1.00	0.5007
Speed	0.0022	0.00120	1	27.83	0.1193
Mobility*NumSources	0.2673	0.14877	1	3453.19	0.0108
Mobility*Obstacles	0.0001	0.00003	1	0.65	0.5689
Mobility*Speed	0.0014	0.00079	1	18.37	0.1459
NumSources*Obstacles	0.0001	0.00007	1	1.52	0.4338
NumSources*Speed	0.0210	0.01169	1	271.23	0.0386
Obstacles*Speed	0.0001	0.00003	1	0.72	0.5515
Mobility*NumSources*Obstacles	0.0002	0.00013	1	3.13	0.3274
Mobility*NumSources*Speed	0.0196	0.01092	1	253.46	0.0399
Mobility*Obstacles*Speed	0.0000	0.00003	1	0.61	0.5776
NumSources*Obstacles*Speed	0.0002	0.00009	1	2.16	0.3805

Appendix E. Node Pair ETE Delay Results

Table E.1: Node Pair ETE Delay Data

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.045526	0.084639	0.034634	N/A
		0.072613	0.036166	0.044756	0.075922
		0.05032	0.085221	0.028315	N/A
		0.07293	0.094559	0.118259	0.045864
		0.058218	0.008041	0.057407	0.072508
	30sources	0.056837	0.104372	0.081278	0.066129
		0.089029	0.043789	0.067377	0.156688
		0.069644	0.100852	0.041113	N/A
		0.080396	0.111721	0.110817	0.054795
		0.074118	0.014116	2.129949	0.124826
RPGM	20sources	0.030268	0.03419	0.004094	N/A
		N/A	0.005435	1.233217	N/A
		0.017886	0.025387	0.012566	N/A
		0.021147	0.026095	0.020063	N/A
		0.013425	0.039319	0.005667	N/A
	30sources	0.04175	0.044939	0.027508	N/A
		N/A	N/A	N/A	N/A
		0.024482	N/A	0.023851	N/A
		0.028389	0.004683	0.026442	N/A
		0.011877	N/A	0.011335	N/A

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.013425	0.005729	0.004155	0.003495
		0.003874	0.002106	0.004961	0.010145
		0.003735	0.010903	0.00741	0.004276
		0.004	0.005579	0.003204	0.005076
		0.005968	0.004202	0.005757	0.002524
	30sources	0.018648	0.006759	0.02028	0.004677
		0.005203	0.009331	0.005877	0.010843
		0.004957	0.009997	0.005685	0.007662
		0.005797	0.007492	0.007375	0.003329
		0.009577	0.007037	0.008341	0.003416

Table E.2: Node Pair ETE Delay Means

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.059922	0.061725	0.056674	0.064765
	30sources	0.074005	0.07497	0.486107	0.10061
RPGM	20sources	0.020681	0.026085	0.255121	N/A
	30sources	0.026624	0.024811	0.022284	N/A

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.0062	0.005704	0.005097	0.005103
	30sources	0.008837	0.008123	0.009512	0.005986

Table E.3: Node Pair ETE Delay Standard Deviations

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.012576	0.037717	0.036143	0.016457
	30sources	0.012045	0.043475	0.919279	0.04837
RPGM	20sources	0.007132	0.01292	0.546808	N/A
	30sources	0.012302	0.028465	0.007459	N/A

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.00414	0.00325	0.001603	0.002973
	30sources	0.005794	0.00145	0.006119	0.003232

Table E.4: Node Pair ETE Delay 95% Confidence Intervals

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
OM	20sources	0.044309	0.0149	0.011804	0.044334
		0.075534	0.10855	0.101544	0.085196
	30sources	0.059052	0.020997	-0.65515	0.04056
		0.088958	0.128943	1.62736	0.16066
RPGM	20sources	0.011827	0.010045	-0.42372	N/A
		0.029535	0.042125	0.933965	N/A
	30sources	0.011352	-0.01053	0.013024	N/A
		0.041896	0.06015	0.031544	N/A

Intra-group node pair

		NoObstacles		ObstaclesPresent	
		Slow	Fast	Slow	Fast
RPGM	20sources	0.00106	0.001669	0.003108	0.001413
		0.011341	0.009738	0.007087	0.008794
	30sources	0.001643	0.006323	0.001916	0.001974
		0.01603	0.009923	0.017108	0.009998

Table E.5: Node Pair ETE Delay ANOVA

Intra-group pair

Source	Sum of Squares	Percent of Variation	Degrees of Freedom	F Ratio	Prob > F
C. Total	0.2027	1.00000	15		
Model	0.1965	0.96915	14	2.24	0.4847
Error	0.0063	0.03085	1		
Mobility	0.0453	0.22331	1	7.24	0.2265
NumSources	0.0170	0.08368	1	2.71	0.3474
Obstacles	0.0108	0.05343	1	1.73	0.4136
Speed	0.0059	0.02892	1	0.94	0.5103
Mobility*NumSources	0.0078	0.03865	1	1.25	0.4642
Mobility*Obstacles	0.0202	0.09977	1	3.23	0.3231
Mobility*Speed	0.0123	0.06050	1	1.96	0.3948
NumSources*Obstacles	0.0083	0.04109	1	1.33	0.4545
NumSources*Speed	0.0060	0.02978	1	0.97	0.5056
Obstacles*Speed	0.0138	0.06805	1	2.21	0.3772
Mobility*NumSources*Obstacles	0.0163	0.08044	1	2.61	0.3530
Mobility*NumSources*Speed	0.0126	0.06230	1	2.02	0.3904
Mobility*Obstacles*Speed	0.0064	0.03137	1	1.02	0.4973
NumSources*Obstacles*Speed	0.0138	0.06786	1	2.20	0.3777

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14. ABSTRACT

Routing protocols designed for wired networks cannot be used in mobile ad hoc networks (MANETs) due to the dynamic topology, limited throughput, and energy constraints. New routing protocols have been designed for use in MANETs, but have not been thoroughly tested under realistic conditions such as node movement, number of sources, the presence of obstacles, and node speed.

This research evaluates the performance of ad hoc on-demand distance vector routing with respect to throughput, goodput ratio, end-to-end (ETE) delay, node pair packet delivery rate, and node pair end-to-end delay. It shows these performance metrics vary significantly according to the choice of mobility model, number of sources, and the presence or absence of obstacles. The mobility model explains 68% of the variation in node pair packet delivery rate. The mobility model explains between 8% and 53% of variation in the other performance metrics. Obstacles explain between 5% and 24% of variation, and have the greatest effect on ETE delay. Finally, the number of sources explains between 8% and 72% of variation in node pair ETE delay, throughput, goodput ratio, and node pair packet delivery rate. The number of sources does not have a significant affect on ETE delay.

15. SUBJECT TERMS

Mobile Ad Hoc Network (MANET), Ad Hoc On-Demand Distance Vector (AODV) Routing, Mobility, Wireless

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					Rusty O. Baldwin, Ph.D. (AFIT/ENG)
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U	U	U	UU	88	(937) 255-6565, ext 4445 (Rusty.Baldwin@afit.edu)

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